TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ERKKA MARTIKAINEN

ELECTRICAL DISTRIBUTION NETWORK ASSET MANAGEMENT FROM THE ASPECT OF AUTHORITY REGULATION

Master of Science thesis

Examiner: Prof. Hannu-Matti Järvinen
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ABSTRACT

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Electrical distribution businesses in Finland are regional monopolies that are regulated by the Energy Authority. Regulation is carried out by requiring Distribution System Operators (DSO) to send annual reports regarding their electrical distribution networks to the Energy Authority. Among other details, DSOs must report all of their owned network assets. The regulation model is evolving, and reporting requirements laid out by the Energy Authority are under constant change. In the recent years, the required data for the annual reports has been increasingly more detailed. Information systems used by the DSOs can be utilized to assist in reporting.

The most recent reporting requirements came into effect in 2016. Network assets that were previously disregarded in the requirements were added to the mandatory reports. As a result, DSOs need to digitize their networks in more detail, which presents a need to develop information systems further.

In this thesis, a multitude of solutions to improve network asset reporting capabilities were designed and implemented to ABB MicroSCADA Pro DMS600 (DMS600), an information system for DSOs. The solutions were introduced in the main DMS600 software, created as additional tools or implemented directly in the system's report definitions. As a result, the developed solutions enabled DMS600 customers to digitize and report network assets that were added in the latest update to the reporting requirements. However, it was also noted that many DSOs have not digitized enough information about their network assets, making it difficult to gather report data.

In the future, network asset reporting of DMS600 could be developed to be more streamlined by automating more steps of the process. In a broader sense, DMS600 could be developed in a more data-driven direction, which would give DSOs more tools to plan and operate their networks.

TIIVISTELMÄ

ERKKA MARTIKAINEN: Sähköverkko-omaisuuden hallinta viranomaisvaatimusten näkökulmasta
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Suomalaiset sähköverkkoyhtiöt ovat alueellisia monopoleja, joiden toimintaa valvoo Energiavirasto. Valvonnassa sähköverkkoyhtiöiltä vaaditaan yhtiöiden sähköverkkoja koskevia vuosittaisia raportteja, joiden osana yhtiöiden tulee raportoida koko sähköverkko-omaisuutensa. Valvontamallia kehitetään koko ajan, ja Energiaviraston raportointivaatimukset muuttuvat jatkuvasti. Viime vuosina raportteihin vaadittavat tiedot ovat muuttuneet entistä tarkemmiksi. Sähköverkkoyhtiöiden tietojärjestelmiä voidaan käyttää raportoinnin tukena.

Viimeisimmät raportointivaatimukset tulivat voimaan vuonna 2016. Sähköverkon komponentteja, joita ei ennen huomioitu valvonnassa, lisättiin osaksi pakollisia raportteja. Lisäyksen seurauksena sähköverkkoyhtiöiden tulee digitoida verkkoonsa enemmän komponentteja, mikä luo tarpeen päivittää tietojärjestelmiä.

Tässä työssä suunniteltiin ja toteutettiin joukko ratkaisuja, jotka parantavat sähköverkko-omaisuuden raportointimahdollisuuksia ABB:n MicroSCADA Pro DMS600 (DMS600) -tietojärjestelmässä. Ratkaisut toteutettiin DMS600:n sovelluksiin, uusina lisätyökaluina sekä suorina muutoksina järjestelmän raporttimäärityksiin. Kehitystyön seurauksena DMS600-asiakkaat saivat mahdollisuuden digitoida ja raportoida komponentit, jotka lisättiin uusimmissa raportointivaatimuksissa. Kehityksen aikana toisaalta huomattiin, että sähköverkkoyhtiöt eivät ole digitoineet kaikista vanhoista verkkokomponenteistaan tarpeeksi tietoja, jonka vuoksi automaattisten raporttien kerääminen voi olla vaikeaa.

Tulevaisuudessa sähköverkko-omaisuuden raportointia DMS600:ssa voisi sujuvoittaa automatisoimalla lisää työvaiheita. Laajemmassa mielessä DMS600-tuotetta voisi kehittää datapainotteisemmaksi, jolloin sähköverkkoyhtiöillä voisi olla käytössään enemmän työkaluja verkkojensa suunnitteluun ja käyttöön.

PREFACE

This thesis was written for ABB Oy (Power Grids, Grid Automation). The examiner of this thesis was Professor Hannu-Matti Järvinen from the Department of Pervasive Computing in Tampere University of Technology and the supervisor of this thesis was M.Sc. Ilkka Nikander from ABB Oy. I would like to thank both the examiner and the supervisor for their guidance during the work on this thesis.

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Erkka Martikainen

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

API	Application Programming Interface
CLC	CORINE Land Cover
CORINE	Coordination of Information on the Environment
DBMS	Database Management System
DMS	Distribution Management System
DMS600	ABB MicroSCADA Pro DMS600
DMS600 NE	ABB MicroSCADA Pro DMS600 Network Editor
DMS600 WS	ABB MicroSCADA Pro DMS600 Workstation
DSO	Distribution System Operator
EEA	European Environment Agency
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
HSB	Hot Standby
HV	High Voltage
IED	Intelligent Electronic Device
LV	Low Voltage
MFC	Microsoft Foundation Classes
MV	Medium Voltage
NCC	Network Control Center
NIS	Network Information System
NPV	Net Present Value
ODBC	Open Database Connectivity
RDL	Report Definition Language
RV	Replacement Value
SCADA	Supervisory Control And Data Acquisition
SQL	Structured Query Language
SYKE	Finnish Environment Institute
SYS600	MicroSCADA Pro SYS600
XML	Extensible Markup Language

1. INTRODUCTION

Electrical distribution businesses in Finland are regional monopolies that are regulated by a regulator, the Energy Authority. Regulation is carried out by gathering annual technical and economic reports from the Distribution System Operators (DSO). The regulation model is constantly evolving and reporting requirements laid out by the Energy Authority are changing. In the recent years, the required data for the annual reports has been increasingly more detailed. As a result, Network Information Systems (NIS) and Distribution Management Systems (DMS) used by DSOs also require constant development, because tools provided by the systems can be used to assist DSOs in generating the annual reports. [1][2]

ABB MicroSCADA Pro DMS600 (DMS600) is an information system developed for DSOs. The most recent reporting requirements for DSOs came into effect in 2016, and DMS600 needs further development to improve its existing reporting capabilities to match the newest authority requirements. Current reporting instructions from the Energy Authority require DSOs to report network assets that DMS600 has no means of digitizing, which leaves DSOs using the system unable to automatically generate the mandatory reports. The contents of the reports affect the profits DSOs are allowed to earn, which creates an economic motive to achieve more accurate reports [2].

The objective of this thesis is to design solutions to enhance asset management and reporting capabilities of DMS600 during the current regulatory period. Electrical distribution networks and the authority regulation model are examined based on literature. Research of the new features is based on current electrical distribution network development trends, public documents by the Energy Authority and feedback from DMS600 customers. The thesis introduces the most important development needs and presents solutions to implement them across the entire DMS600 system.

This thesis consists of seven chapters. Chapter 2 establishes relevant knowledge about electrical distribution networks and the operational environment of DSOs. It also presents an introduction to information systems that exist in electrical distribution. Chapter 3 introduces the ABB MicroSCADA Pro DMS600 software. It includes details of the general architecture of the product portfolio and describes the individual programs that make up the DMS600 product. Reporting tools are also described. Chapter 4 presents the identified development needs of DMS600 and Chapter 5 describes the developed solutions. Chapter 6 evaluates the solutions that were presented in the previous chapter and presents ideas for future development. Finally, Chapter 7 concludes the thesis with final remarks on the process.

2. ELECTRICAL DISTRIBUTION NETWORK ASSET MANAGEMENT

The electric power system of Finland consists of power plants, the national transmission network, distribution networks and consumers. The power system is a part of the inter-Nordic power system which consists of connected power systems of Finland, Sweden, Norway and Eastern Denmark. In addition, the Finnish power system is connected to Russia and Estonia via transmission links that utilize direct current, making it possible to transmit electricity between systems that operate under different electrical principles. This thesis focuses on distribution networks, which are presented in more detail in this chapter. [3]

2.1 Electrical distribution networks

Electrical distribution networks are parts of the electric power system that supply the electrical energy from the national transmission network to consumers. Electrical distribution networks consist of high voltage (HV) networks (sometimes referred to as regional network [3]), medium voltage (MV) networks, low voltage (LV) networks and substations where electricity is transformed between different voltage levels. Substations can be either primary substations between HV and MV networks or distribution substations between MV and LV networks. Electrical distribution networks are operated by distribution system operators (DSO). A summary of electrical distribution network structure is presented in Figure 2.1. [1]

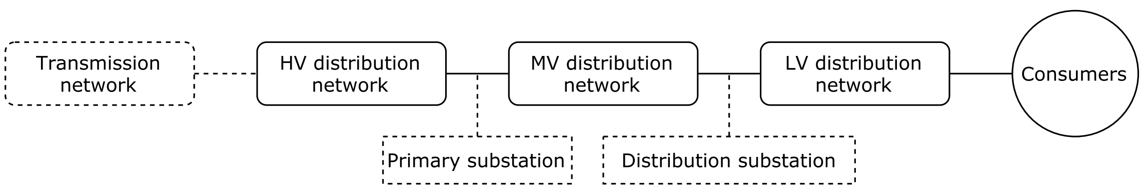

Figure 2.1 *Structure of electrical distribution networks.*

Electrical energy is transmitted and distributed by power lines that connect power production, consumers and necessary intermediary network components together.

Depending on their structure, conductors used in the power lines are categorised as overhead lines or cables. Cables are usually considered to be conductors that have their electrical parts insulated from their surroundings by some other material than air. From the perspective of regulation, the difference between overhead lines and cables is determined by installation practices: overhead lines are built outside on top of utility poles, while cables are placed either in cable trenches that are dug in the ground or submerged in water to reduce possible mechanical damage. [4]

Installation of underground cables is more expensive than installation of overhead lines. The cost of underground cable installation depends strongly on the environment: sometimes digging the cable trench may cost more than the cable itself if the installation work disrupts functions of society or the work is laborious due to difficult soil properties. Additionally, the costs are further driven up by accessories, joints and cable terminals that are required to connect the cable to the electrical distribution network. Installing an underground cable usually costs three to ten times more than installing an overhead line. On the other hand, cables provide more protection from environmental factors such as weather, making transmission and distribution of electricity more reliable. [4]

The majority of HV and MV networks are built as overhead lines while LV networks are mostly built as cables. However, in cities and urban areas it is common to install underground cables in the MV network, too. Recently the installation of underground cables outside cities and even outside urban areas has become a lot more common because of increased reliability requirements, landscape protection and the desire to limit electromagnetic fields. [1][4]

Conductors are considered primary components in an electrical distribution network, along with other essential electrical components like transformers. In addition to primary components, secondary systems and equipment are considered to be a crucial part of electrical distribution networks. Secondary systems and equipment can include various information systems operated by DSOs or automation devices located at substations. [1]

2.2 Electrical distribution business

Building multiple parallel electrical distribution networks that carry out the same function would be economically infeasible. To prevent this, DSOs are assigned regions in which they build and operate their networks. Only one DSO can build and operate an electrical distribution network in a region, making electrical distribution business in Finland a regional monopoly (natural monopoly). DSOs have an obligation to maintain and develop their networks according to customers' needs and to assure good quality of electricity. The pricing of electricity is also required to be fair and the prices need to take the effectiveness and reliability of the electric power system into account. [5]

Main stakeholders in the electrical distribution business can be divided into four categories: asset owners, asset managers, service providers and consumers. Asset owners own the electrical distribution networks and handle the economic duties related to the business. Asset managers handle the core responsibilities related to an electrical distribution network, such as economic and technical planning and customer service. Usually the asset owner and the asset manager are the same entity (DSO), but a company could focus only on asset management duties by operating several different distribution networks. [1]

Service providers are companies that support DSOs in their operations. Unlike DSOs, service providers operate in the free market. Examples of common services include constructing new parts of electrical distribution network, fixing faults and carrying out maintenance work. Outsourcing services has been a trend in the past few decades, and it has been effective from the DSOs' point of view. As a result of the trend, service providers have been able to concentrate their resources in highly specialized research and equipment. If this had not been the case, DSOs would have had to try achieve the same profiency with significantly smaller resources. [1]

2.3 Authority regulation

Electricity Market Act in the Finnish law requires companies to separate electrical distribution businesses from businesses that produce or sell electrical energy. Separation means that electrical distribution business must have separate income statements and balance sheets. In addition, the juridical form, organization and decision making in electrical distribution companies has to be independent of selling or producing electrical energy. The reason for the separation is to support a healthy and functioning electricity market and to prevent unprofitable businesses from compensating their losses by gaining income from monopoly businesses. [5]

Lack of competition in the natural monopoly gives DSOs no incentive to improve their services or keep their prices reasonable. In order to prevent mismanagement, electrical distribution business in Finland is regulated by a regulator, the Energy Authority. Regulation carried out by the Energy Authority includes both technical and economic aspects. The regulation focuses on DSOs' profits and on ways how

DSOs can make their operation more cost-effective. Each DSO is assigned a reasonable return, which means the maximum profit the DSO is allowed to make. If the reasonable return is exceeded, the DSO must return the money exceeding the limit to its customers. On the other hand, if there is a deficit, the DSO may charge its customers more. [1] [2]

Since 2005, authority regulation has been carried out in four-year regulatory periods. Every regulatory period has its own regulation model, which is a collection of rules and formulas that apply to every DSO. Details of each regulation model are presented in the regulatory methods, which is a public document by the Energy Authority. The ultimate goal of a regulation model is to make every DSO operate effectively and price their electricity distribution fairly. Regulatory periods also act as time limits for DSOs to handle their deficit or surplus regarding their reasonable return, as the amounts are calculated at the end of a regulatory period and the possible compensation has to happen during the following regulatory period. [2]

The current regulatory period is active from 2016 to 2019, but the same regulation model will also be used from 2020 to 2023 in the following regulatory period [5]. The purpose of using same regulation model is to provide DSOs continuity and predictability in their network planning activities between regulatory periods [2].

Regulatory models and their methods are based on practical experiences from previous regulatory periods, and the Energy Authority aims to make the model better after every regulatory period [5]. In addition, the Energy Authority utilizes expert reports and statements as background material when preparing new iterations of regulation methods and guidelines [2].

2.3.1 New Electricity Market Act

In 2013, a new edict of the Electricity Market Act was enacted. The enactment introduced major changes to the electrical distribution reliability requirements. Since 2013, DSOs have had to plan, build and maintain their distribution networks to not have interruptions related to weather, such as fast winds or heavy snowfall. Article 51 of the Electricity Market Act states that a single occurrence of electricity distribution interruption in an area that belongs to a town plan may go on for for a maximum of six hours, while interruptions in other areas may go on for 36 hours. These limitations do not concern customers in remote islands, customers whose electricity consumption has been less than 2 500 kWh in the previous three years, or customers in cases where the investment cost for better reliability would be unreasonable due to long distance. [6]

Because it would not have been possible for DSOs to fulfil the new reliability requirements immediately, article 119 of the Electricity Market Act specifies a transition period for improving electrical distribution networks to the desired level of reliability. The transition period is defined by the relative amount of customers in the DSO's designated area that fulfil the requirements of article 51. The schedule for the transition period is as follows:

- 50% of customers by the end of 2019 (excluding summer houses)
- 75% of customers by the end of 2023 (excluding summer houses)
- 100% of customers by the end of 2028 (including summer houses).

DSOs may apply to be granted extra time for improving their networks if their need to install underground cables greatly exceeds the average amount of underground cable installations of other DSOs. If a very good reason is found, deadlines of 75% and 100% coverages may be postponed until the ends of 2028 and 2036 respectively. Applications to postpone deadlines need to be submitted by the end of 2017. [6]

To ensure that DSOs are actively trying improve the reliability of electricity distribution in their networks, the Electricity Market Act requires DSOs to create a network development plan and update it every two years. Development plans include detailed actions that systematically improve the reliability of the DSO's electrical distribution network and move it towards the goals set by articles 51 and 119 in the Electricity Market Act. Network development plans and the regular updates to them are delivered to the Energy Authority. [6]

According to data published by the Energy Authority, many DSOs have decided to fulfil the new reliability requirements by focusing their investments on improving cabling rates in their electrical distribution networks. Table 2.1 shows the development of cabling rates from 2011 to 2016 on a national level. It also shows estimates of future cabling rates for the deadline years that have been specified in the Electricity Market Act. The estimates are based on distribution network development plans that DSOs have delivered to the Energy Authority. [7]

The overall cabling rates have grown by about 1 percentage points per year in both MV and LV networks. According to the network development plans, the rate of growth will increase considerably in the next 12 years, as the overall cabling rate is supposed to go from 18.8% to 47% in MV networks and from 42.0% to 65% in LV networks. However, it should be noted that changing overhead lines to underground

Table 2.1 Development of cabling rates in Finnish electrical distribution networks [7].

Year	Cabling rate in MV networks, %	Cabling rate in LV networks, %
2011	12.3	37.5
2012	13.2	38.6
2013	14.5	39.0
2014	16.4	40.8
2015	17.6	41.4
2016	18.8	42.0
2019	28	49
2023	37	57
2028	47	65

cables is not the most optimal solution to electricity distribution reliability problems in all situations. For example, in environments outside town areas it's often sufficient to move overhead lines to open areas such as roadsides, making disruptions caused by trees less likely. [7]

2.3.2 Network asset reporting

In practice, regulation is carried out by annual reports that DSOs deliver to the Energy Authority. The reports contain information about network assets and values of financial and technical key figures. All of the required regulatory data is defined in the regulation methods that the Energy Authority publishes before the beginning of each regulatory period. This thesis focuses on network asset reports and does not cover financial or other technical key figures of DSOs. [2]

Network asset reports are delivered to a web portal provided by the Energy Authority. Deadline for the reports is by the end of March, and they represent the status of the DSOs' networks at the end of the previous year. Reports consist of detailed asset information that is separated to different categories that correspond to network components' logical functions in electrical distribution networks. Examples of the categories include transformers, conductors and switching components. Categories are further divided by voltage levels. Individual network assets are finally differentiated by their type and size. The following information must be reported for each network asset type: [2]

- quantity of assets currently in use
- average age of assets currently in use
- quantity of expansion investments (assets bought in the previous year)
- quantity of replacement investments (replaced assets in the previous year)
- quantity of removed assets in the previous year
- planned lifetime of asset (if applicable).

Expansion investments are investments that are used to connect new customers to the electrical distribution network. For example, building entirely new parts of distribution network is considered an expansion investment. Replacement investments, on the other hand, are investments that replace older network components in order to improve the performance of the electrical distribution network. Expansion investments and replacement investments are reported separately because the Energy Authority must supervise DSOs' obligation to develop their networks. [8]

The Energy Authority uses the gathered network asset information to calculate the value of every DSO's distribution network. The value of the network owned by a DSO is a major factor in determining the DSO's reasonable return. In the regulation model, the prices of network components are standardized and the prices are used to calculate the adjusted replacement value (RV) for each DSO's network. However, from the regulator's point of view, the value of the network needs to be adjusted to correspond with the actual net value of the network. For example, a network component that is two decades old cannot be considered to be as valuable as a new component of the same type. In order to solve the need to differentiate between old and new components, the Energy Authority also calculates the adjusted net present value (NPV) of every DSO's network annually. [2]

The adjusted replacement value for a single network component type is obtained by using the formula

$$RV_i = unit\ price_i \times quantity_i\ , \tag{2.1}$$

where RV_i is the combined adjusted replacement value of all network components of type i, $unit\ price_i$ is the price of a single network component of type i and $quantity_i$ is the total amount of network components of type i. The unit prices are determined by the Energy Authority's regulation method document and they are the same for every DSO, even though component prices may vary between actual network asset vendors. Expanding Formula 2.1, the adjusted replacement value for the entire network operated by a DSO is calculated with the formula

$$RV = \sum_{i=1}^{n} RV_i \ , \tag{2.2}$$

where RV is the adjusted replacement value of all assets in the network. [2]

Adjusted net present value takes the age information of network components into account and it's calculated with the formula

$$NPV = \sum_{i=1}^{n}((1 - \frac{average\ age_i}{lifetime_i}) \times RV_i) \ , \tag{2.3}$$

where NPV is the total adjusted net present value of the electrical distribution network, $average\ age_i$ is the calculated average age of all reported components of type i and $lifetime_i$ is the expected lifetime of component type i. If a component is older than its designated lifetime, it is regarded only as old as the lifetime. Component lifetimes are selected by DSOs from a list provided by the Energy Authority. [2]

It can be said that the authority regulation model is practically based on trust. The Energy Authority does not have the resources to verify that all received data is correct, and DSOs gather and calculate their regulatory data independently. DSOs have responsibility for the validity of the submitted regulatory data. [2]

2.3.3 Underground cables in the regulation model

As noted in Subsection 2.3.1, investing in underground cabling has increased in recent years, and the amount of investments will increase even more in the next decade because of new electricity distribution reliability requirements. Cabling rate growth means that the adjusted replacement value of electrical distribution networks will also rise. The RV of a DSO's underground cable network consists of two major parts: conductors and cable trenches. While the cost of conductors stays rather predictable, the cost of excavating cable trenches is dependent on environmental factors. Despite the variance in operating conditions, every DSO needs to achieve the desired reliability levels regardless of the conditions in their assigned region. Energy Authority takes different environmental conditions into account by assigning cable trenches to four different classes: easy, ordinary, difficult and extremely difficult. [2]

Easy conditions exist in areas where there is little traffic and excavating the ground is easily done. In practice, this means rural areas where not much infrastructure exists. Ordinary conditions have some existing infrastructure, such as buildings and streets at outskirts of towns. This means that installing underground cables disrupts activities in its surroundings. Difficult conditions exist in areas that have a lot of traffic and are active during the day and in the evening. Difficult conditions also include situations where excavating is difficult for other reasons, such as rocky terrain. Extremely difficult conditions are found in populous areas where excavations require very expensive special arrangements in order to be successful. Areas belonging to the extremely difficult environmental condition are generally only found in the centers of the biggest cities in Finland. [2]

As with other network assets, cable trenches are assigned value-determining unit prices by the Energy Authority [2]. Table 2.2 presents the unit prices of each environmental condition.

Table 2.2 *Unit prices of cable trenches in different environmental conditions [2].*

Environmental condition	**Cable trench unit price**
Easy	10 700 €/km
Ordinary	24 200 €/km
Difficult	77 200 €/km
Extremely difficult	151 200 €/km

When comparing the cable trench prices with each other, it can be seen that excavating a cable trench in difficult conditions can be over seven times more expensive than excavating a cable trench in easy conditions. Therefore determining correct classes for cable trenches can make a great difference in a DSO's reasonable return.

The value of an underground cable network belonging to a DSO is calculated by assigning the DSO an average unit price per one kilometer of underground cabling. The calculated price describes the average excavation conditions within the DSO's network area. When the Energy Authority performs RV and NPV calculations, the average unit price is added to the unit prices of underground cables. [2]

DSOs are obligated to report the actual lengths of their underground cable trenches in the aforementioned four environmental conditions to the Energy Authority as a part of their network asset reports. The cable trenches must be in actual use, which means that they must contain cables that distribute electricity within the DSO's network. In previous regulatory periods, it has been possible for DSOs to estimate the lenghts of cable trenches by performing calculations on conductor lengths, but from 2016 to 2023, only the actual lengths of cable trenches are accepted by the Energy Authority. [2]

In the first regulatory periods, environmental classes of cable trenches were chosen by written definitions that corresponded with underground cable locations. However, according to many DSOs, the written definitions were too ambiguous and the classification process did not provide equal treatment between DSOs. In the current regulatory period, environmental classes are based on town plan areas, CORINE Land Cover (CLC) data and written definitions by the Energy Authority [2]. Town plan area data and CLC data are spatial data sets provided by the Finnish Environment Institute (SYKE). The data sets are freely available on SYKE's website. [9][10]

The town plan area data set by SYKE contains the outer borders of Finnish town plans as vector-based polygons. The data set is distributed in ESRI Shapefile format and updates to the data are made annually. ESRI Shapefile (or shapefile) is a data format by Environmental Systems Research Institute (ESRI) and it's used to store attribute information and nontopological geometry of spatial features [11]. An example of town plan areas in the data can be seen in Figure 2.2. [12]

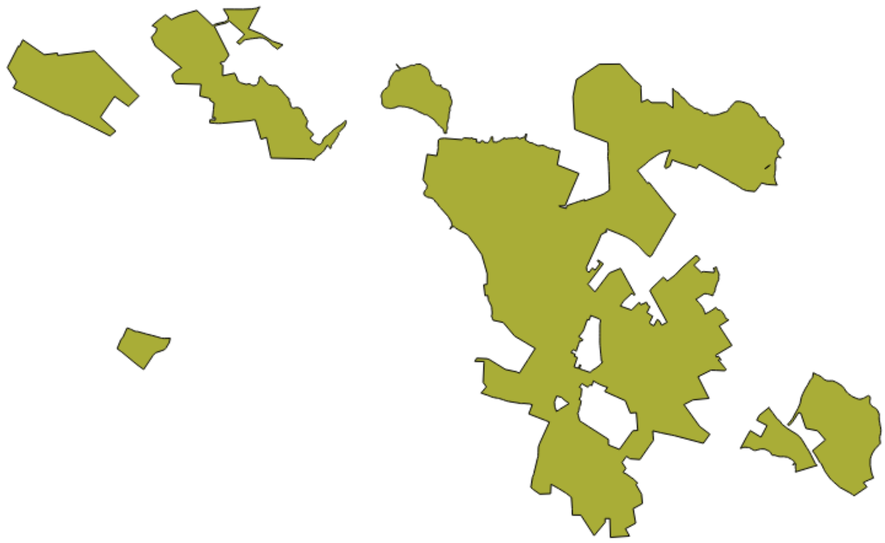

Figure 2.2 *Polygons representing town plan areas in the data set provided by SYKE.*

The CLC data set provides information on land cover and land use in Finland. The data is a part of the CORINE (Coordination of Information on the Environment) programme that was initiated by the European Union in 1985 and since then taken over by the European Environment Agency (EEA) [13]. There are two main data sets in CLC that can be used for spatial analysis with cable trenches: a raster data set with $20m \times 20m$ accuracy produced for national use in Finland and a generalized vector data set with 25 ha accuracy produced for EEA. The raster data is provided in GeoTIFF format and the vector data is provided in ESRI Shapefile format. Both data sets were last updated in November 2014, with the source material being from

2011, 2012 and 2013. An example of the raster data is shown in Figure 2.3. [14]

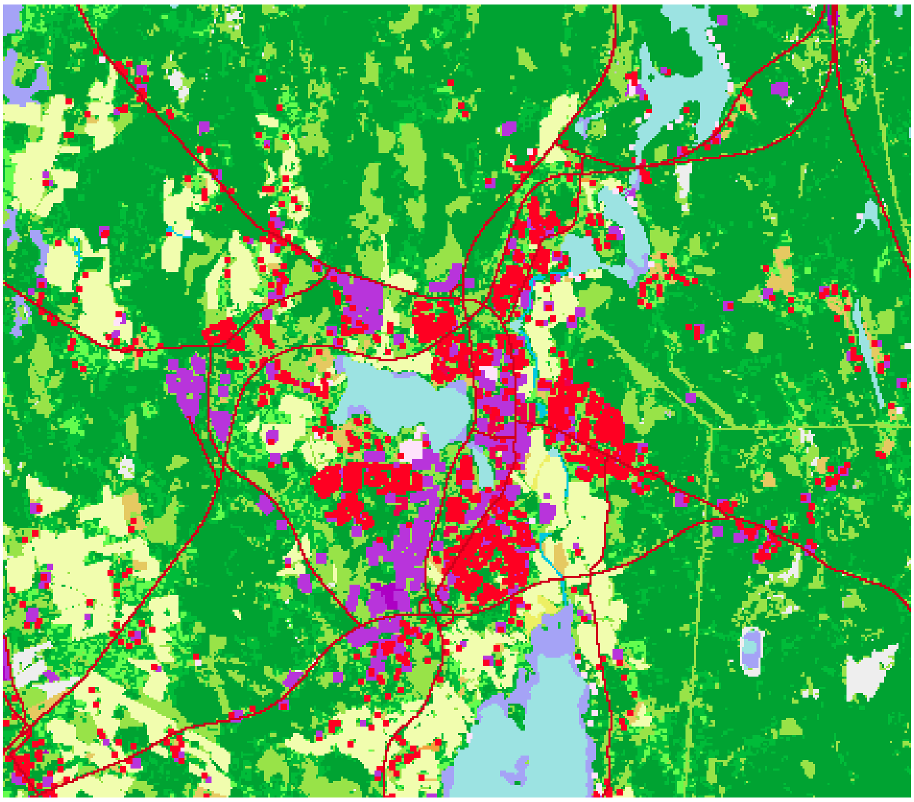

Figure 2.3 *A screenshot of CLC raster data by SYKE.*

CLC data is based on classes that describe the environmental conditions at different locations. There are five main classes: artificial surfaces, agricultural areas, forests and seminatural areas, wetlands and water. The main classes are divided to second level that has 15 subclasses, which are further divided into a third level that has a total of 44 subclasses to describe geographical locations. Level 1 classes are distinguished by single-digit numbers, level 2 classes by double-digit numbers and level 3 classes by triple-digit numbers. For example, airport areas belong to CLC class 124. The first digit denotes the main class (artificial surfaces), the second digit denotes the level 2 subclass (industrial, commercial and transport units) and the third digit denotes the level 3 subclass (airports). [15]

CLC classes are represented in the data differently depending on the data set format. In the raster data set, classes are determined by each pixel. One pixel is an area of $20m \times 20m$, and the pixel's color determines the type of the area's land use. In the vector data set, areas are polygons and CLC information is stored in each polygon's metadata. [14]

Energy Authority uses town plan areas and level 3 CLC subclasses in determining excavation conditions of cable trenches. The current regulation methods do not specify the required data set format explicitly, but the first instructions related to utilizing open spatial data sets mention that raster data should be utilized. A summary of environmental condition criteria can be seen in table 2.3. As seen in the table, only seven different classes out of the 44 are used. Furthermore, the classes used to determine extremely difficult conditions are the same as in difficult conditions. In these cases, written definitions by the Energy Authority determine the environmental conditions. The reason for using additional definitions is that no publicly available data set is able to differentiate conditions of difficult and extremely difficult areas between each other. [9]

Table 2.3 *Criteria of determining environmental conditions of cable trenches [9].*

Environmental condition	**Criteria in data sets**
Easy	Areas outside town plan areas
Ordinary	Areas inside town plan areas Class 112 (Discontinuous urban fabric)
Difficult	Class 111 (Continuous urban fabric) Class 121 (Industrial or commercial units) Class 122 (Road and rail networks) Class 123 (Port areas) Class 124 (Airports) Class 332 (Bare rock)
Extremely difficult	Class 111 (Continuous urban fabric) Class 121 (Industrial or commercial units) + Written definitions

Class 122 in the CLC data set provides another exception to the classification. In general, areas belonging to class 122 represent road and rail networks, but the actual environmental condition is determined by the conditions that exist in the immediate surroundings of a road or a railway. If several different conditions exist on different sides of the road or the railway, the easier condition is always chosen. However, if the road or railway area is exceptionally large, it can be considered a difficult area by itself. [9]

Even though using CLC data in determining environmental conditions is considered more fair than simple written definitions, not all DSOs are satisfied with the practice. DSOs have been concerned that the data set is not updated often enough and it's difficult to utilize. As an effort to keep the practice more relevant, the

Energy Authority provides a possibility for DSOs to propose corrections to areas that are not presented correctly in the CLC material. Errors in the material must be clear and verifiable in large areas. Minor errors are considered to compensate each other, as some errors might be advantageous to DSOs. For example, an underground cable trench might be located in a difficult area in the CLC material, but due to inaccuracies in the data, digging might actually be easier and cheaper than expected. [16][2]

2.4 Distribution automation

Operating an electrical distribution network is essentially real-time process control where parts of the process are geographically far apart. The role of information systems in modern-day electrical distribution networks is significant. The information systems are commonly referred to as distribution automation, which can be divided into five different levels: utility level, network control center (NCC) level, substation level, feeder level and customer level. An overview of the information systems and their connectivity with each other can be seen in Figure 2.4. [1]

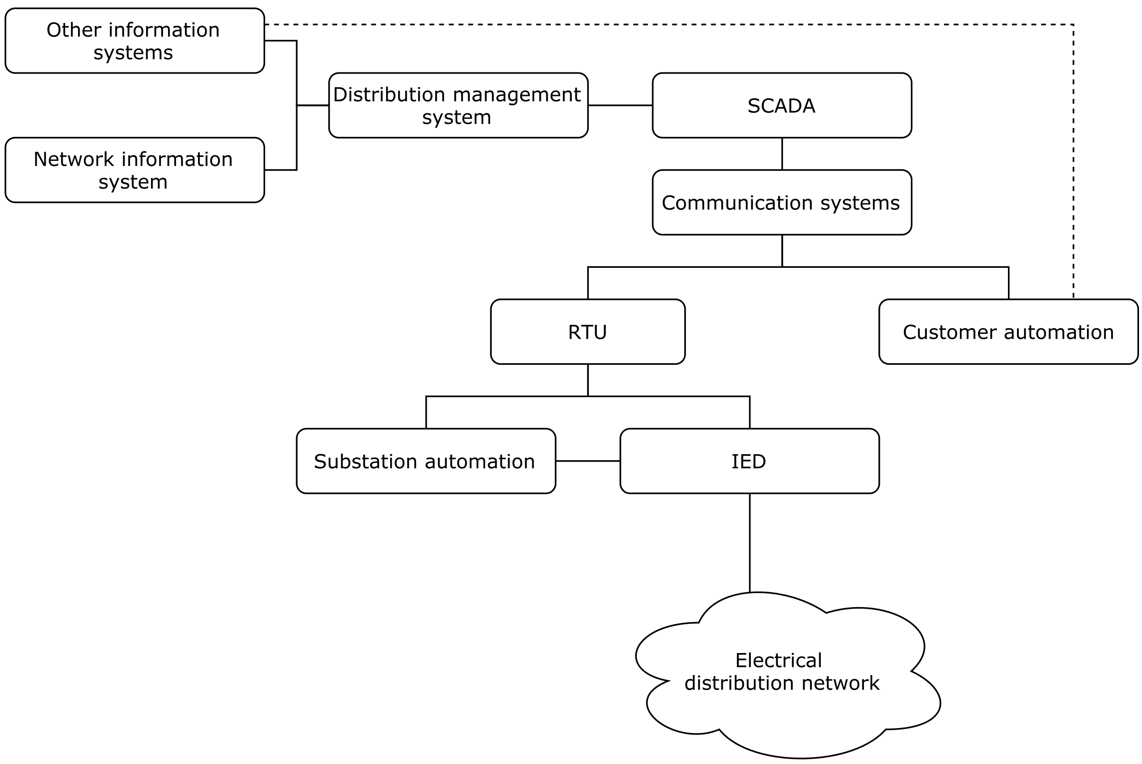

Figure 2.4 *Overview of information systems in electrical distribution networks (adapted from [1]).*

The utility level of distribution automation consists of systems that DSOs use to plan their networks and to perform complex or repetitive tasks such as simulating their networks. The systems utilized on this level are SCADA systems (Supervisory Control And Data Acquisition), Distribution Management Systems (DMS) and Network Information Systems (NIS). These systems are presented in more detail in Subsections 2.4.1 and 2.4.2. In addition, other systems such as customer information systems might be used. In NCCs, only SCADA and DMS software are utilized, as the purpose of NCCs is limited to monitoring the state of the network and performing remote controlled switch operations in fault situations or during planned maintenances. [1]

Substation level includes Intelligent Electronic Devices (IEDs) that provide network protection, measurements and control possibilities at primary substations. Measurements collected by IEDs are sent to NCCs via Remote Terminal Units (RTUs), which connect substations to communication networks. Substations can also contain automation related to voltage regulation, which in practice means sending control signals to transformers located at the primary substation. Feeder level automation means the remote control of disconnectors, data transfer from fault indicators and voltage and current measurements in the network. [1]

Customer level automation consists of remote meter reading and load control management. Automated meter reading (AMR) is usually used for billing, but the energy consumption data might be used in other systems on the utility level information systems as well. Load control management means that a customer's electricity consumption may be switched on and off depending on the willingness of the customer and the overall load of the electrical distribution network. [1]

The focus of this thesis is on information systems on the utility level, namely the network information systems. Therefore this thesis will not present further details on the other levels of distribution automation, such as communication protocols, embedded software of IEDs or AMR technology.

2.4.1 Network Information System

Network Information System (NIS) is an information system that's used for electrical distribution network planning and documentation. NIS is the main tool in digitizing electrical distribution networks and their components. Data is typically stored in a relational database, which contains the network model that can be used for the majority of a DSO's planning, operation and analysis tasks. Other applications may also use the network database. Data in the database consists of network asset information such as locations, technical details and maintenance history. The user interface of a NIS is based on a geographical representation of the network, along with more detailed electrical diagrams of some network parts, such as substations. [1]

Many network planning activities are optimization tasks where factors such as switching component locations and switching states, conductor sizes and the overall shape of the electrical distribution network play a role. While NIS's provide some tools to solve these problems, linear algorithms and routines are rarely geared towards these complex optimization tasks. However, simpler planning tasks, such as comparing sizes of power lines from an economic perspective, are very often handled by NIS's. After desirable plans have been made, a NIS can also produce relevant documents about the execution of the plans, such as maps and information about costs and responsible personnel. [1]

2.4.2 SCADA and DMS

SCADA is an information system that monitors and adjusts the state of a process. In the context of electrical distribution networks, SCADA monitors the switching states of components and provides real-time measurements from the network. Alarms and other events can be generated from the measured data, possibly requiring personnel in the network control center to take action. SCADA can also be used to remotely control network components. [1]

Measurements for SCADA systems in electrical distribution networks are usually taken on primary substations, but some remote-controlled switches and fault indicators outside substations might also be available. Detailed information about customers, components and loads in MV and LV networks is not included. [1]

Distribution Management System (DMS) is an information system that provides versatile tools to support network operation. While SCADA systems monitor the electrical distribution network and display measured information, they rarely contain any functionality to perform more complex analysis tasks. Conversely, the main feature of a DMS is the ability to utilize data from many different sources to analyze and solve problems related to network operation. The main use cases of DMS software are tasks that support network state monitoring, network operation planning and fault management. [1]

An important feature of a DMS is maintaining the switching state of the network (also referred to as topology) and displaying it on a geographical map. As opposed to SCADA, DMS usually includes information of MV and LV networks as well. Another important feature is performing real-time electrical calculations and analysis tasks which are based on a digitized network model combined with information received from SCADA. The network model is usually the same which was digitized in a NIS, making NIS and DMS closely related in DSOs' activities on the utility level. Finally, tracking the locations of field crews is also a widely-used feature in DMS products. [1]

3. ABB MICROSCADA PRO DMS600

MicroSCADA Pro DMS600 (DMS600) is an information system for DSOs. The system is developed by ABB and it is a part of the MicroSCADA Pro product portfolio that also includes MicroSCADA Pro Control System SYS600 (SYS600), which is a SCADA software, and MicroSCADA Pro SYS600C, which is an industry grade computer for substation environments. DMS600 consists of a Distribution Management System called DMS600 Workstation (DMS600 WS) and a Network Information System called DMS600 Network Editor (DMS600 NE). An overview of the MicroSCADA Pro software architecture can be seen in Figure 3.1. [17]

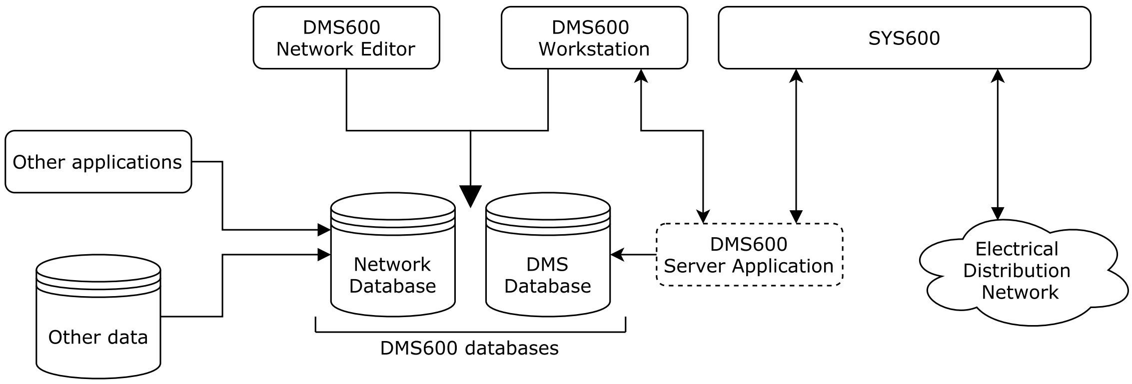

Figure 3.1 *Overview of MicroSCADA Pro software architecture (adapted from [18]).*

DMS600 WS and DMS600 NE were originally developed in the 1990s under different names by Versoft Oy, a software company based in Tampere, Finland. The company was acquired by ABB in 1997 and the products were integrated into ABB's MicroSCADA product line. [19]

DMS600 runs on the Microsoft Windows operating system. It is mostly implemented in C++ and its user interface utilizes the Microsoft Foundation Classes (MFC) library, which is an object-oriented wrapper for accessing Microsoft Windows application programming interfaces (APIs) [20]. In addition to the two main information systems, DMS600 includes background services and tools that are implemented in C# [18].

3.1 DMS600 Workstation

DMS600 Workstation (DMS600 WS) is the Distribution Management System in the MicroSCADA Pro product portfolio. DMS600 WS supports the operation of MV and LV electrical distribution networks in DSOs' network control centers and it's used in conjunction with a static network model and a SCADA system that gathers real-time process data. Real-time process data is provided to DMS600 WS by DMS600 Server Application, which is a background service that communicates with SYS600 and between DMS600 WS instances. Network component switching states, ongoing faults and other information related to network operation are stored in an operational database, the DMS database. The network is presented in the user interface as a geographical representation along with background maps. An example of the user interface of DMS600 WS is presented in Figure 3.2, which depicts a situation of maintenance outage planning. [17][21]

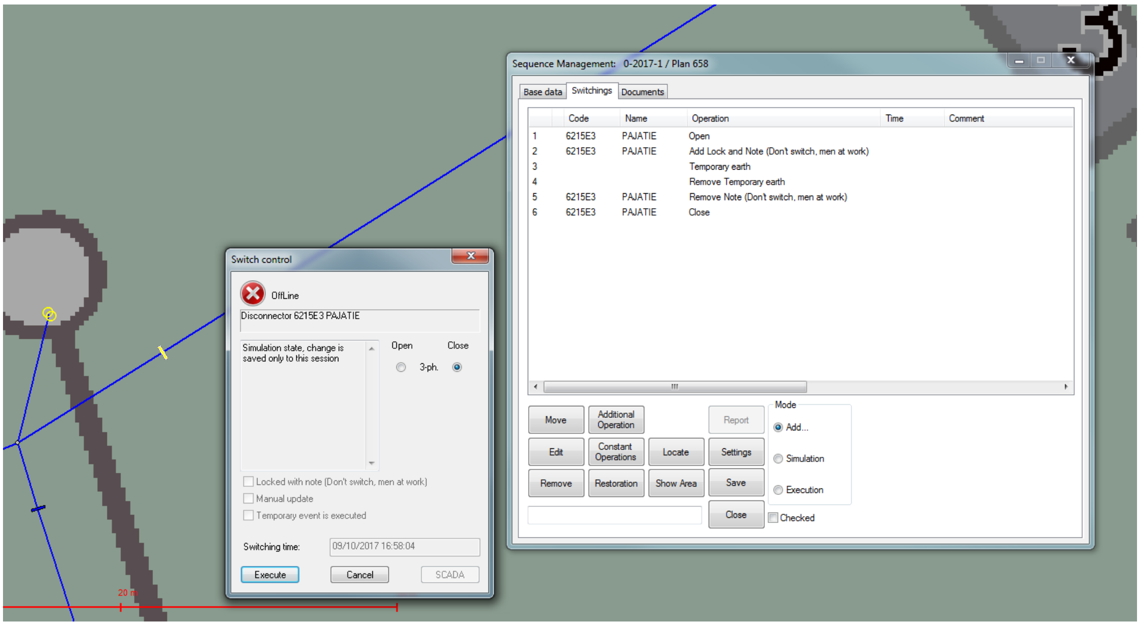

***Figure* 3.2** *Screenshot of ABB MicroSCADA Pro DMS600 WS, demonstrating a situation where a network operator plans a maintenance outage.*

Major features of DMS600 WS include network topology management, real-time network analysis and calculations, network simulation, switching planning, fault management, coordinated voltage level control, field crew management and customer service integration. Outages in the network can also be stored and reported for further analysis. [17]

3.2 DMS600 Network Editor

DMS600 Network Editor (DMS600 NE) is a Network Information System that's used to view and edit the information in the network database. The stored information contains technical details and the general structure of the electrical distribution network on MV and LV level. Technical details include component-specific physical properties and maintenance information, while network structure means the geographical locations of network assets and their connectivity to each other. By knowing both technical details and network structure, topology management and calculations are made possible. [17]

Other information can be saved to the network database as well. For example, data from a customer information system can be exported to the database. By connecting the individual customer data to customer nodes in the network, customer information can be viewed while editing the network in DMS600 NE. [17]

Network database information may also be utilized by other applications. Network asset reporting and data processing related to reports are an example of such applications. [18]

DMS600 NE presents the electrical distribution network on a geographical map. Network information is edited with dialogs that pop up when clicking network components on the map. The user interface of DMS600 NE is presented in Figure 3.3.

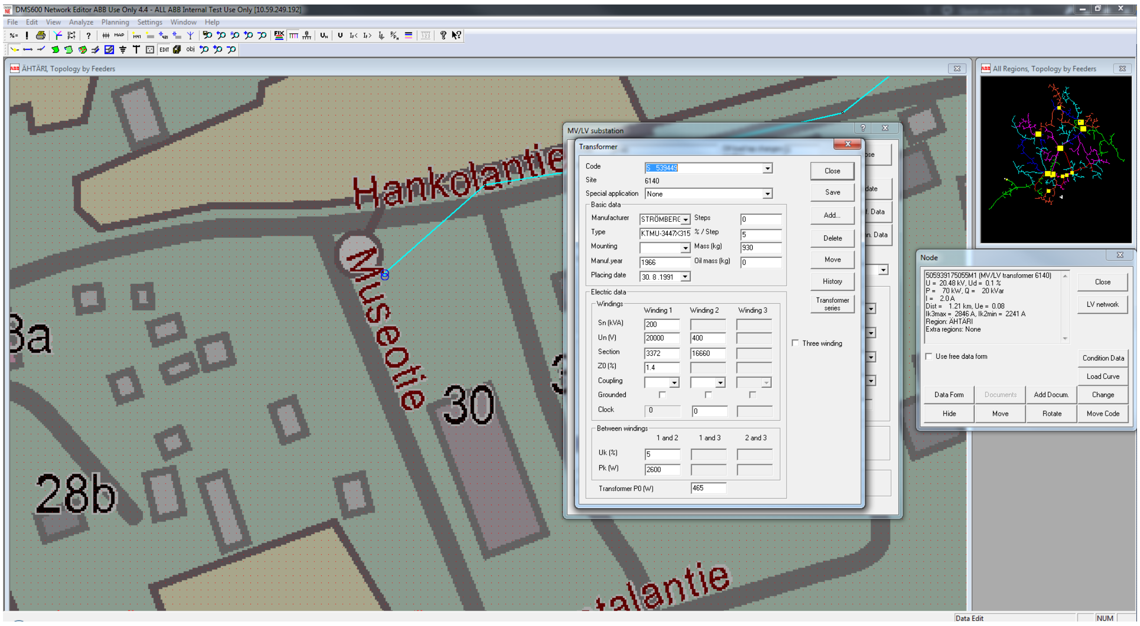

Figure *3.3 Screenshot of ABB MicroSCADA Pro DMS600 NE.*

In addition to network editing and information management, DMS600 NE can be used for network planning, where changes to the network are sketched and evaluated but not necessarily committed to the network database. Other features include electrical calculations, network protection analysis and reliability analysis. DMS600 NE also acts as an administrative tool for configuring important settings of both DMS600 systems. Examples of these settings include network symbol and color definitions and background map settings. [17]

3.3 Database solutions

DMS600 utilizes relational databases that are queried with Structured Query Language (SQL). The default Database Management System (DBMS) for DMS600 installations is Microsoft SQL Server, but Oracle DBMS is also supported in customer installations. Connections to the databases are made by using an Open Database Connectivity (ODBC) interface provided by the Microsoft Foundation Class Library framework [21][22]. [23]

In Figure 3.1, network and DMS databases were presented as separate entities. However, DMS600 also supports using a single database that contains both the static network information and the operational data needed for distribution management. In customer installations, databases are often divided in order to limit the amount of data in a single database, preventing possible unnecessary slowness in network operation [18]. [21]

DMS600 can be configured to support a Hot Standby (HSB) configuration for increased reliability. In a HSB configuration, only one database instance and its related DMS600 background services are "hot", meaning that they actively process data and perform functionalities. Other instances are "warm", which means that they are ready to start processing data as soon as the "hot" instance becomes unavailable. In practice, the configuration on database level is done by using multiple network and DMS databases and setting up built-in replication provided by the chosen DBMS. DMS600 software handles the switchover situations. [21][23]

3.4 Reporting Services

As presented in Subsection 2.3.2, Finnish DSOs have a multitude of reporting duties. Since the entire electrical distribution network along with its asset condition information and fault history is saved to DMS600 databases, it's convenient to gather the report data from them. Finnish DMS600 customers only use Microsoft SQL

Server as their DBMS, so the asset reports have been implemented with SQL Server Reporting Services (SSRS). [18]

SSRS is a reporting platform by Microsoft that provides reporting functionality from many different data sources. SSRS includes tools to create, manage and deliver reports, and a possibility for developers to customize and extend existing reporting functionalities. SSRS tools are fully integrated with SQL Server tools and components, and they work within the Microsoft Visual Studio environment. [24]

Reports for SSRS are done as report definitions that contain data source information, data retrieval queries, expressions, parameters and layout where the results are displayed. Report definitions are created in Report Definition Language (RDL), which is based on Extensible Markup Language (XML). In DMS600 report development, report definitions are created with Business Intelligence Studio, which is a Visual Studio extension [18]. [25]

SSRS reports are installed and accessible on a SSRS report server that's installed alongside DMS600 databases. The report server internally stores reports, report-related items, resources, schedules and subscriptions. Reports are accessed through a web-based service. The user interface of the DMS600 report server with some example reports can be seen in Figure 3.4. [25]

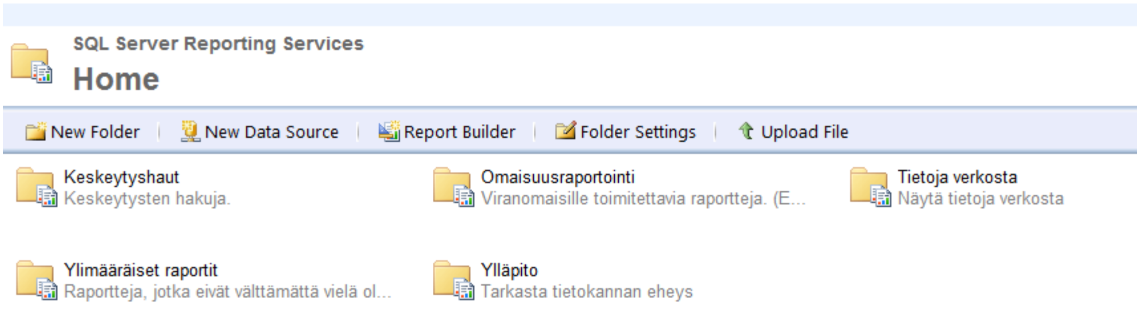

Figure 3.4 *Front page of DMS600 reporting services, based on SQL Server Reporting Services.*

DMS600 reports are installed to customer environments with tools made by ABB. First, all necessary reports are bundled together with a tool called CreateReportPackage. Afterwards, the bundled reports can be set up on the customer report server with the InstallReports tool, which is a graphical application installed by the DMS600 installer. InstallReports scans the DMS600 installation, finds the relevant databases, sets up the data source linking required for the reports and runs necessary set-up scripts in the customer database. [26]

4. DEVELOPMENT NEEDS OF DMS600

The majority of asset management and reporting capabilities of DMS600 are based on the previous regulatory period that lasted from 2012 to 2015. New regulation methods came into effect in 2016, and since then DMS600 has not been updated with functionality that would fulfil all of the requirements laid out by the Energy Authority. It's in DSOs' best interests to report their assets as accurately as possible, because maximizing the net present value of the network also maximizes the amount of the DSO's reasonable return. This chapter assesses the development needs of DMS600 from the perspective of network asset management and reporting.

Requirements for new DMS600 features were gathered by examining public documents by the Energy Authority and by gathering feedback from DMS600 customers. There is no official and consistent communication channel between the Energy Authority and information system providers, which means that evaluating the need for changes has to be done independently by companies that develop network information system and distribution management system software. However, because the reports greatly affect DSOs' businesses, DSOs also examine the regulation methods in detail and notice possible shortcomings in their chosen software. As a result of both ABB's internal and external evaluation, a list of development needs was formed.

Identified development needs were divided in three categories: addition of new network components, implementation of cable trenches and overhaul of existing network asset reports. The three categories are presented in more detail in Sections 4.1, 4.2 and 4.3.

4.1 New network components

Regulation methods of the currently active regulatory period contain new network assets that have not been included in asset type lists in earlier regulatory periods [2][27]. DMS600 does not support managing all of the assets acknowledged by the regulatory model. Some network components are completely new in the current regulatory period, and some have not been implemented to the system during previous regulatory periods for other reasons.

When customer requirements were analyzed, it was decided that new network components must be included as a part of new asset management additions. If DSOs are not able to digitize all of their network assets, the assets cannot be automatically included in the DSOs' asset reports either. The following network components found in the regulation methods are not implemented in DMS600:

- conductor joint
- indoor termination
- outdoor termination
- medium voltage cable box
- MV network voltage regulator (20 kV/20 kV)
- LV network voltage regulator.

Conductor joints and terminations are essentially points in the electrical distribution network where a conductor ends and another begins. Conductor joints extend the same type of conductor even further, while termination means a point where a cable ends. Outdoor terminations are points where an underground cable changes to an overhead power line and indoor terminations are points where a cable is connected to another network component, such as a switchgear inside a substation. [4]

MV cable boxes are components that allow the branching of a single MV cable to several MV cables. The branching is done inside a cabinet that protects the cables from weather and provides easier access for maintenance. Finally, voltage regulators are components that keep the voltage of the electrical distribution networks high enough to provide good quality of electricity even in remote parts of the network. More detailed explanations of the unimplemented network components and their electrical properties are not in the scope of this thesis. [4]

From the perspective of network asset management, new components must be able to be added to the digitized network model and their information must be able to be edited. Removal must also be possible. Adding to the network means that the new components can be connected to existing network parts in the same way that they are connected in the real electrical distribution network. The new components must also support existing analysis tools and calculations without causing malfunctions in DMS600 WS or DMS600 NE.

4.2 Cable trenches

As mentioned in Subsection 2.3.3, in previous regulatory periods it was possible to gather the lengths of MV and LV underground cables and multiply them with coefficients to estimate cable trench lengths within a DSO's designated network region. However, the Energy Authority only accepts actual cable trench lengths during the ongoing regulatory period. [2]

DMS600 does not have a feature to digitize cable trenches. As a result, DSOs cannot report accurate lengths of cable trenches by utilizing data from the DMS600 network database. It was decided that introducing the concept of cable trenches to DMS600 is essential to the software's asset management capabilities. The new development need can be divided to two major parts: modeling of cable trenches in the network database and performing environmental condition analysis based on digitized data.

4.2.1 Modeling of cable trenches

Cable trenches are non-electrical network assets. This means that adding cable trenches to DMS600 network database does not require any immediate changes to existing network analysis tools or topology management. From the perspective of data, cable trenches are entities that link together one or more cables and a geographical route. In addition, cable trenches can include data that describes other properties, such as the physical structure of the trench.

As a part of requirement analysis, minimal functional requirements of cable trenches were drafted. The requirements were quite similar to the requirements of other new components: users of DMS600 NE must be able to create, edit and remove cable trenches with new network editing tools. In addition, it was determined that cables in both MV and LV networks should be able to be assigned to cable trenches. Assigning cables to trenches means that information of which cable is laid in which cable trench is stored.

Creating cable trenches in DMS600 customers' network databases was seen as an additional challenge. Most DMS600 customers own hundreds of kilometers of underground cables, and digitizing such a large amount of cable trenches by hand is very laborious work. For this reason, it was deemed necessary to create an import tool that populates the DMS600 network database with initial cable trench information by using existing cable locations as input. The purpose of the initial information is to provide a starting point for customers to digitize the finer details of their cable trenches.

4.2.2 Environmental condition analysis

Calculating cable trench lengths in different environmental conditions was seen as the final requirement of introducing cable trenches to DMS600, as the calculations are the reason cable trenches are needed in the first place. The basic principle of environmental condition analysis is presented in Figure 4.1.

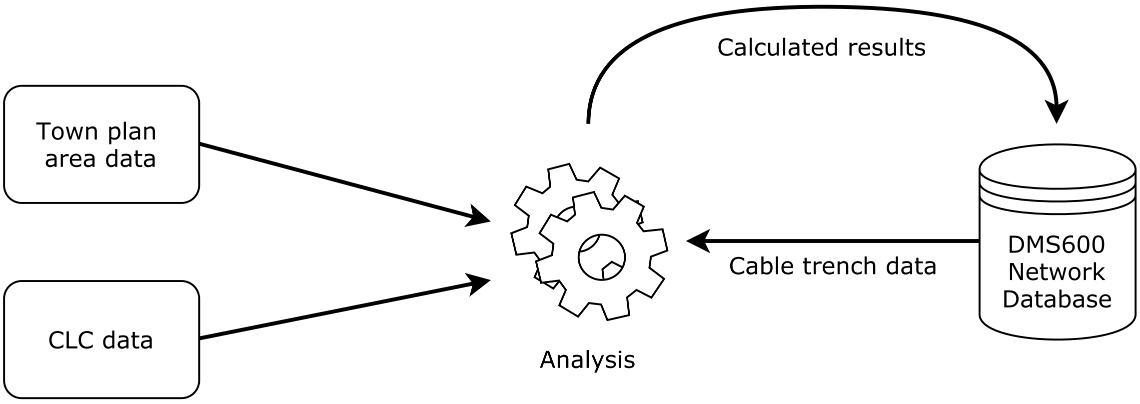

Figure 4.1 *Basic principle of environmental condition analysis.*

The inputs for environmental condition analysis are cable trenches in the network, a town plan area data set and a CLC data set. The output of the analysis produces the length of each cable trench in ordinary and difficult environmental conditions. The conditions can be limited to only two, because extremely difficult conditions are not verifiable with data sets and easy conditions are simply the ones that do not belong to any of the other conditions.

The actual analysis is a geometrical problem that has to be independently solved for each cable trench. In two-dimensional space, a cable trench can be thought as a sequence of line segments. Each line segment has a starting point and an ending point that correspond to geographical locations. When each line segment is laid on top of a map that consists of empty areas and used areas (town plan or CLC), it can be determined how much the line segment intersects the used areas and how much it does not.

An example of an analysis situation with a single cable trench is visualized in Figure 4.2. In the visualization, a town plan area is shown in a light color and a difficult CLC area is shown in a darker color. A black line representing a cable trench passes through both areas and the type of the line shows the correct environmental condition.

The cable trench in the example consists of three segments. The first and the third

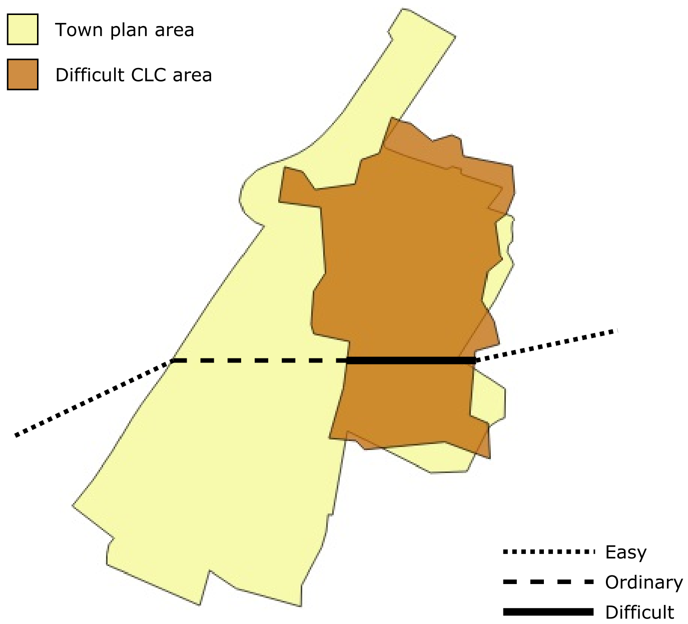

Figure 4.2 *Visualization of environmental condition analysis. The types of the line segments represent the correct environmental condition that should be assigned to each part of the cable trench.*

segments are not in any area specified by a data set, so they are considered to be in easy environmental conditions. However, the second segment can be further split into two parts, one of which belongs to ordinary conditions and one to difficult conditions. Therefore it can be concluded that the analysis needs to be able to manage situations where a single segment is divided between multiple CLC or town plan areas. Additionally, in cases where a difficult CLC area and town plan area overlap on the map, the more difficult environmental condition must be chosen.

4.3 Network asset reports

Examining existing DMS600 network asset reports showed that they do not correspond well with the reports demanded by the Energy Authority. In addition to the unimplemented components described in Section 4.1, several shortcomings in asset categories and in the presentation of results were found. For these reasons, overhauling network asset reports was regarded as a mandatory improvement to the asset management capabilities of DMS600.

The main development need in the network asset reports was considered to be adding and fixing DMS600 report categories so that they would match the categories in the regulation methods. While it has been possible for DMS600 customers to categorize components quite freely for a long time, the categories have been created independently by the customers. As a result, the categories in customers' databases rarely match the categories in the regulation methods, and there are dissimilarities between different customers' component categories as well. If there is a mismatch in the categories, manual work must always be done in order to enter the report data properly.

Another problem with categories was noticed in some existing DMS600 asset reports. Many of the DMS600 asset reports from the previous regulatory periods were simple listings of network components by type, while they actually need to be bundled by some criteria. An example of such situation can be seen in Figure 4.3, which shows a part of a report detailing conductors in the network.

Maakaapeli	1kvAX95	7		7.57	40
Maakaapeli	AHXCM120	1070		31.60	40
Maakaapeli	AHXCM185	180		36.00	40
Maakaapeli	AHXCM70	3845		13.74	40
Maakaapeli	AHXW120	26921	2	13.20	40
Maakaapeli	AHXW150	34376		4.83	40
Maakaapeli	AHXW185	43425		2.05	40
Maakaapeli	AHXW185V	10457		1.82	40

Figure 4.3 *DMS600 underground cable report from earlier regulatory periods.*

In the figure, each row represents one conductor type in the DSO's network. The columns from left to right are conductor type, conductor code, total length of conductors in use, total length of removed conductors in the previous year, average age and the planned lifetime. While the report gives insight into individual conductors, it's not in the format that the Energy Authority expects to receive asset information in. From the regulator's perspective, underground cables must be categorized by their sizes only. Conductors of different types but same size must be bundled together so that their lengths are summed and average ages are calculated appropriately. [2]

With the current DMS600 reports, DSOs must perform the calculations manually, which weakens the appeal of using DMS600 asset reports. The presented problem occurred with other asset types as well, which meant that a comprehensive inspection of reports was needed.

Another identified requirement to DMS600 reporting was the inclusion of asset ownership information. Some DSOs have digitized network components that are owned by other entities, but still exist in the DSOs' electrical distribution networks.

DMS600 reports need to differentiate network assets owned by the reporting DSO and other companies, because DSOs are only supposed to report their own property.

Finally, it was noted that the layout of the DMS600 asset reports was also quite different from the layout of the Energy Authority's web portal. As an attempt to streamline the reporting process, reworking the appearance of DMS600 reporting services was deemed a necessary change.

5. DEVELOPED SOLUTIONS

This chapter presents solutions that were developed to provide solve problems presented in Chapter 4. The implementation process was an iterative cycle where requirements were regularly assessed and prototype solutions were evaluated. The main principle of evaluating various implementation alternatives was to produce a working solution as fast as possible while trying to minimize dependencies on other parts of the system. Dependencies with older parts of the system were considered problematic, because the system contains some legacy code that can cause unwanted technical debt in the future. However, as the software architecture of DMS600 is monolithic, some dependencies were mandatory in order to implement the desired new functionality.

Many of the development needs in Chapter 4 are related to customers' abilities to digitize their networks in better detail. As the tools for digitizing the network are found in DMS600 NE, it was logical to implement the majority of the new features in the network information system. Features related to processing large amounts of data were developed as additional tools that utilize the DMS600 network database. Finally, some solutions related to improving reports were implemented directly to report definitions in SQL Server Reporting Services.

5.1 Network component changes

Several changes to DMS600 network components were made in order to improve the digitization capabilities of the software. Network components described in Section 4.1 were implemented and some changes were made to existing components as well. The new components were implemented purely for asset management purposes. Electrical properties of the components were only evaluated from the perspective of existing analysis tools, which were not allowed to malfunction because of changes in the network model.

Implementation of each new component consisted of designing new C++ classes and database tables. The C++ classes include functionality to read and write relevant information to the network database, present dialogs based on the Microsoft

Foundation Class Library framework to the user and handle the internal logic of saving, loading and displaying data. Additional work went into editing various parts of the legacy code to enable the new components in the first place. More detailed information about network component changes is presented in the following subsections.

5.1.1 General changes

Better handling of asset ownership was proposed as an improvement to DMS600 in Section 4.3. In order to fulfil the requirement, ownership settings were added to every DMS600 network component. The settings consist of owner name and owner information. Owner name is intended to be used in network asset reports and it can only be accessed in the user interface by predefined (but configurable) values, such as "Own" and "Other". Owner information is free text that DMS600 customers can use if they want to describe additional details about the owner.

Due to development time constraints, owner settings could not be implemented in the user interface for the majority of network assets. However, on database level every asset is populated to be owned by the DMS600 customer by default. The ownership of each asset can also be changed via Free Data Form, which is a DMS600 feature that lets users inspect and edit network component database rows directly.

General changes related to component reporting types were done as well. As mentioned in Section 4.3, DMS600 components can be categorized to various types to make a distinction between different kinds of components of the same nature. The type values are often customized in every installation environment, and they do not correspond with types in the regulation methods.

The options to solve the problem were either to force customers to change their database contents to match the regulation methods or provide an additional way to fill in the type information. The latter option was chosen to give customers more freedom in their network documentation work. As a result, new reporting type settings were added to some component data forms.

MV/LV substation data form in DMS600 NE is one of the changed dialogs where the new setting was added. The new setting on the dialog is presented in Figure 5.1. Before adding the new setting, a customer might have had a construction type "POLE" or "ONE POLE" assigned to the MV/LV substation. The Energy Authority requires distinction between 1-pole, 2-pole and 4-pole mountings, so while the structure type might be quite easy to deduce manually, generating automated reports for many different customers would have been difficult.

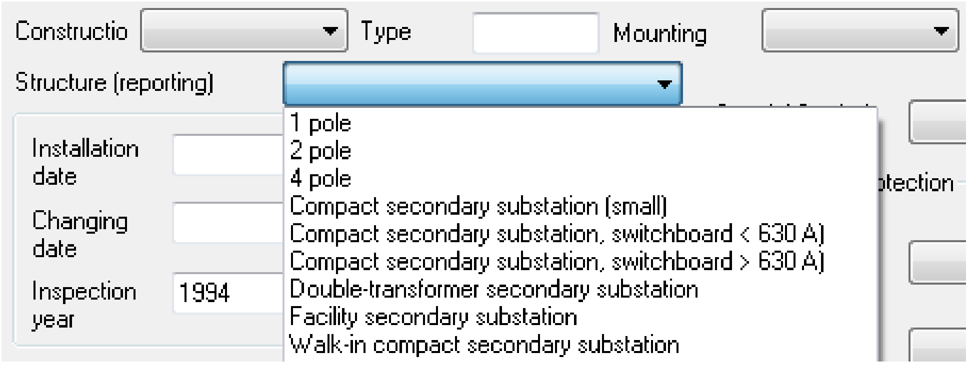

Figure 5.1 *New reporting type field implemented for MV/LV substation components in DMS600 NE.*

The developed solution requires customers to fill the information of reporting type setting fields for every affected component in their network. However, reporting type fields can be populated easily with an SQL script if it's known which reporting categories the old component types belong to. To ease the adaptation of the change, surveys with print-outs of all distinct component types affected by the change were sent to customers. In the survey, customers had the possibility of assigning each old component type to a reporting category. With the survey results, a database populating SQL patch could be created.

5.1.2 Conductor joint

Digitizing conductor joints has technically been possible in DMS600 NE for many years. Users have been able to create conductor joints as nodes anywhere in the network without the possibility to add any information to them. Unfortunately, this was not enough for asset reporting purposes, because the Energy Authority requires more information than the amount of nodes in the network.

Existing conductor joint nodes were revamped to include new components. Conductor joint components are created like any other component in the network, and they have a simple data form dialog which allows users to edit the asset information of the component. The new conductor joint data form is shown in Figure 5.2.

From the perspective of asset reports, the most important field on the dialog is the installation date. The date can be used to calculate the average age of all conductor joints, which is required in the asset reports. The investment type field can be used to differentiate between expansion investments and replacement investments that were detailed in Subsection 2.3.2.

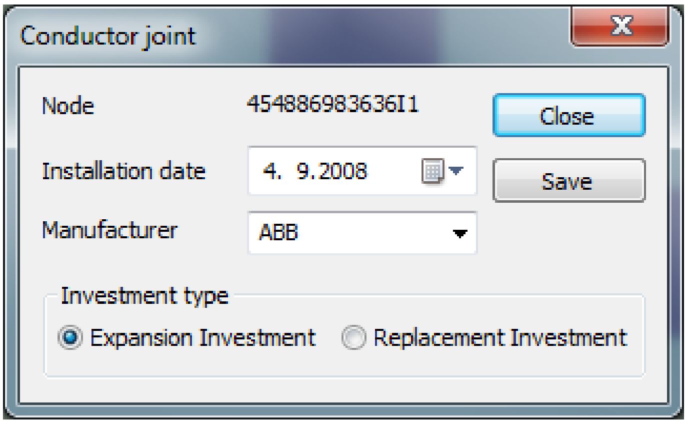

Figure 5.2 *New conductor joint data form in DMS600 NE.*

In addition to creating the new component type, a database patch was created to populate customer databases with new conductor joint components by using the older conductor joint nodes as input. If customers had documented the installation years of the surrounding conductors, the conductor joints could be populated with the same installation dates as well. This minimized the manual work that needed to be done by the customers.

5.1.3 Termination

Indoor and outdoor terminations are network components that exist in every real electrical distribution network, but have not been a part of the DMS600 network model during earlier regulatory periods. There were two main implementation alternatives to get report data of indoor and outdoor terminations:

1. Add a database column to flag existing network components, such as substation feeders, to be included in indoor or outdoor termination reports because terminations are attached to them in real networks.
2. Create entirely new components terminations in the network and use their data in indoor or outdoor termination reports.

Option 1 had the benefit of being very fast to implement, but as a drawback it would not have taken into account situations where individual terminations have been created in remote parts of the network, because a relevant component to attach the termination to might not exist. Additionally, the installation date for the termination could differ from the installation date of the component that contains it.

Option 2 was regarded to be more time-consuming to implement, but it was also acknowledged that implementing a new network component would provide the possibility to fill in more asset information that could be used to generate better reports. After evaluating the alternatives, option 2 was chosen.

A new component, termination, was created in the DMS600 network model. Terminations can be set to be either indoor terminations or outdoor terminations, and the setting can be used to discern the types in the reports. Information of terminations is edited with a new data form dialog, which is presented in Figure 5.3. As with conductor joints, installation date and investment type settings are also included on the dialog.

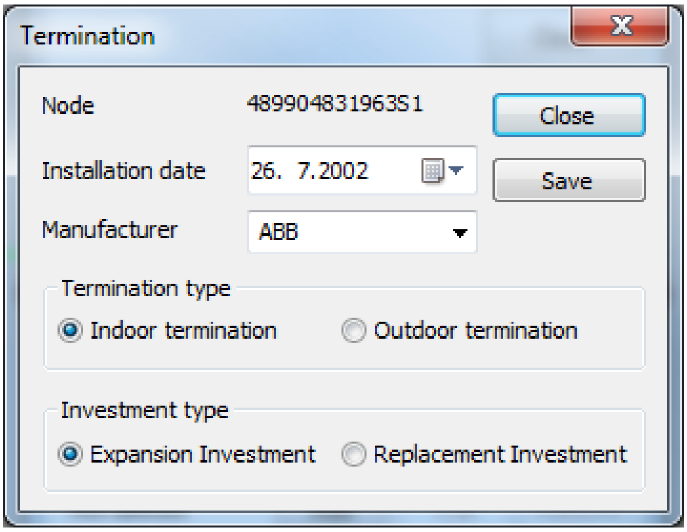

Figure 5.3 *Data form for the new termination component in DMS600 NE.*

The components can be created in the network as new nodes like any other component, or as part of substation feeders. A button was added to substation feeder dialog to open the data form presented above, giving users a possibility to digitize indoor terminations to substations without breaking the network topology in the process. From the perspective of reports, the method of creating the component does not matter.

5.1.4 Medium voltage cable box

Medium voltage cable boxes are components that branch a cable to several more cables. It was noticed during requirement planning that the concept is quite similar to low voltage boxes that already exist in DMS600 networks. Low voltage boxes have a cable going inside, and there are several cables coming out with fuses in each of them. Medium voltage boxes have no switching components, but there are indoor terminations in each cable instead.

Low voltage boxes were used as a reference component to create a new component, medium voltage cable box. From users' perspective, medium voltage cable boxes consist of a main cable box node, cables inside the box, indoor terminations in each cable that enters the box and a background diagram. While creating medium voltage cable boxes, users are prompted how many cells they want the cable boxes to include. A screenshot of a medium voltage cable box is presented in Figure 5.4.

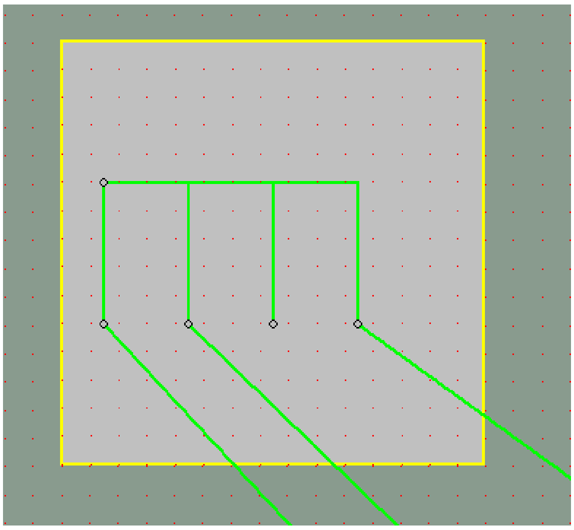

Figure 5.4 *Medium voltage cable box with four cells on the DMS600 NE map. The node in the top left corner is the node containing the information of the medium voltage cable box, while the other nodes are automatically generated indoor terminations.*

Asset management information related to medium voltage cable boxes is saved in the main cable box node. Like other components, installation dates and investment types can be set.

5.1.5 Voltage regulators

Even though the focus of the needed features was in asset management, voltage regulators are components that affect the electrical calculations that are performed as part of different analysis tasks. This meant that the electrical properties of the components could not be overlooked. There were two alternatives in implementing MV network and LV network voltage regulators:

1. Add a property to existing transformers that identifies them as voltage regulators instead of ordinary transformers.

2. Create entirely new components in DMS600 and use their data in asset reports.

Option 1 had the advantage of being quick to implement, but it lacked the modeling of real-world functionality where voltage is analyzed and adjusted by the regulator. However, it would still have been implemented in transformers and therefore voltage calculations could have been performed to some degree. On the contrary, option 2 would have modeled a real-world voltage regulator, but implementing the functionality from the perspective of electrical calculations would have been time-consuming and possibly difficult.

Voltage regulators were chosen to be implemented with option 1. It was not seen as a good use of development time to create a completely new electrical component in DMS600 when the task at hand is asset management improvement. In addition, existing DMS600 customers had little or no voltage regulators in their networks, which would have made implementation efforts impractical.

MV network voltage regulators were implemented as an additional setting in primary transformer data, while LV network voltage regulators were implemented as a special application setting in MV/LV transformers. The added settings are presented in Figures 5.5 and 5.6.

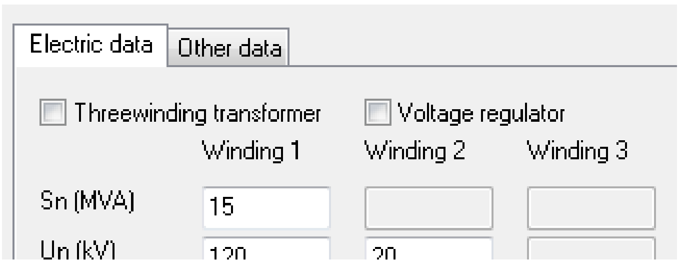

Figure 5.5 *New voltage regulator setting on the primary transformer data form in DMS600 NE.*

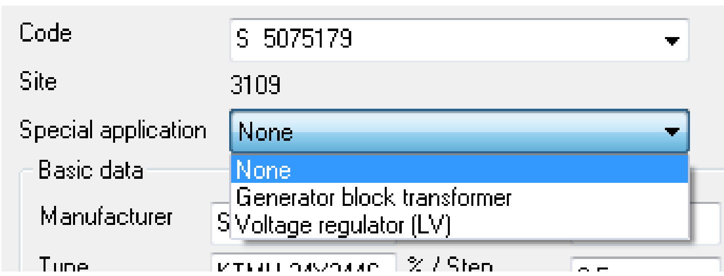

Figure 5.6 *Special application setting on MV/LV transformer data form in DMS600 NE.*

Both primary transformers and MV/LV transformers support network topology analysis and calculations. If the voltages and other electrical information of the regulators are set correctly, the implementation will cause no issues in the existing network. Installation dates and other relevant asset information can be directly retrieved from the data of the transformer components.

5.2 Section routes

In order to fulfil the requirement of introducing cable trenches to DMS600 NE, the concept of section routes was created. Section route is an entity that includes a geographical route and one or more parts of MV or LV line sections in the DMS600 network. Cable trenches are a subtype of section routes, and the section route concept can later be expanded to other types as well, such as a group of overhead lines.

Section routes are stored in the DMS600 network database, and they are shown on the DMS600 NE network map as multi-point lines, similar to MV and LV networks. Section routes were not implemented to DMS600 WS at all because introducing the concept was only done for the purpose of asset management, which is not a responsibility area of DMS software.

Creation and editing of section routes is done with new tools implemented in the existing toolset of DMS600 NE and processed with additional tools that utilize the network database. All of the new tools are described in the following subsections.

5.2.1 Section route editing tools

Section routes can be edited with two new tools that were created in DMS600 NE: the section route creation tool and the section route selection tool. The tools were added to the toolbox of DMS600 NE as a part of other network editing tools, as shown in Figure 5.7.

Figure 5.7 *DMS600 NE toolbox with new section route tools emphasized. The tool on the left is the section route creation tool and the tool on the right is the section route selection tool.*

Section route creation tool is used to lay out the initial geographical points of the section route. The creation sequence is initiated by left-clicking a point on the

DMS600 NE network map, points are added with additional left clicks and the creation is finalized by right-clicking the point where the section route is meant to end. After confirming creating a new section route, the user is presented a section route data form dialog, an example of which can be seen in Figure 5.8.

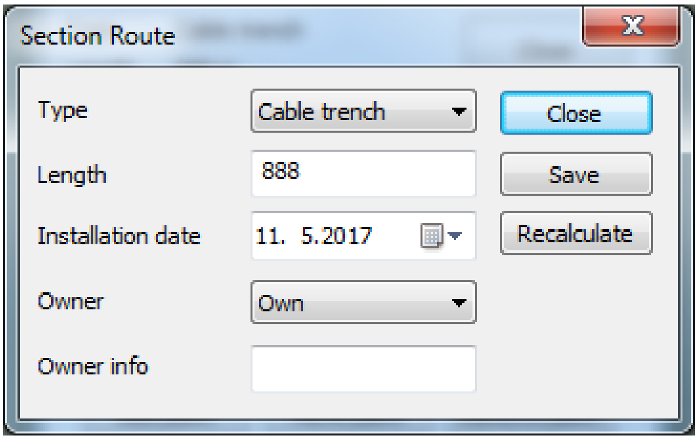

Figure 5.8 *Section route data form dialog in DMS600 NE.*

Users can inspect and edit section routes by selecting them on the DMS600 NE network map while having the section route selection tool active. When a section route is selected, an edit dialog capable of all section route functionality is shown to the user. A selected section route and its edit dialog is presented in Figure 5.9.

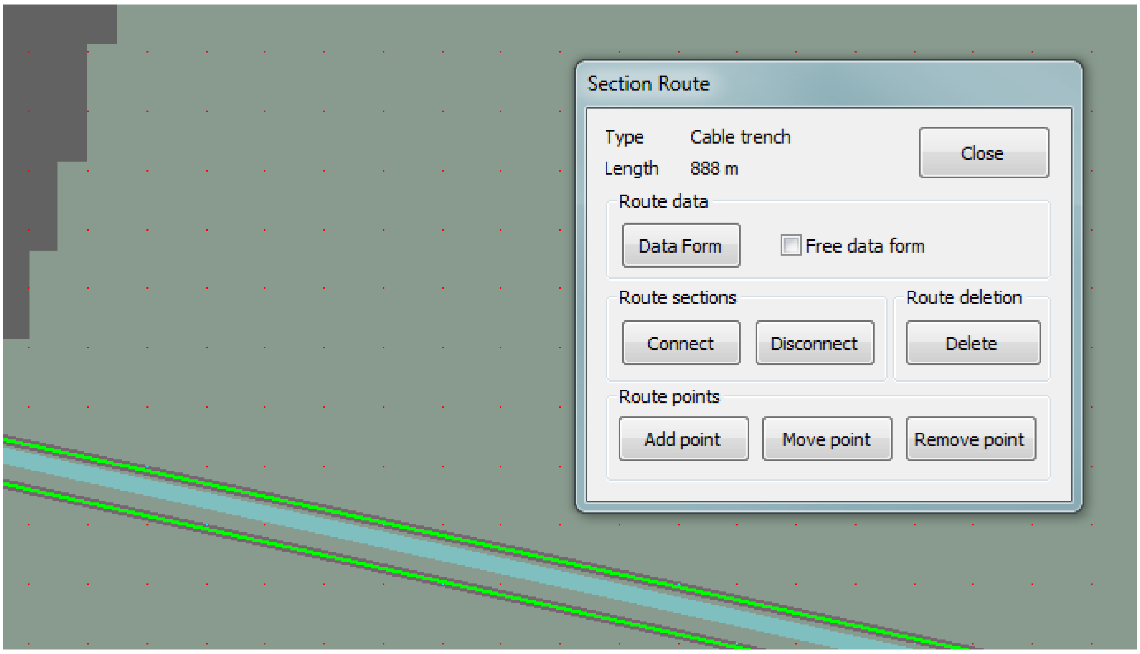

Figure 5.9 *A section route, two MV cables and the section route editing dialog in DMS600 NE. The thick middle line is the section route, and the two highlighted lines on its both sides are cables that are connected to the section route.*

Parts of line sections in MV and LV networks can be added as part of a section route with Connect and Disconnect buttons on the edit dialog. Each MV or LV section can only belong to one section route. Connected sections are highlighted when the section route is selected on the map. The route point controls can be used to edit the geographical shape and location of the section route.

Section routes are not loaded by default when DMS600 NE is started because of performance reasons. Instead, they are loaded into memory when users attempt to utilize the new section route tools for the first time during a DMS600 NE runtime session. Section routes can also be dropped out of memory after editing has finished and they are not needed.

5.2.2 SectionRouteGenerator

A tool that imports preliminary cable trench data to the network database was described in 4.2.1. The tool, called SectionRouteGenerator, was implemented during the creation of the section route concept. The main DMS600 NE software was seen as an unnecessarily heavy program to run script-like imports in, so a standalone additional tool was regarded as a better implementation option. As internal C# libraries that handle DMS600 network database operations had already been created by ABB, C# was selected as the tool's implementation language.

SectionRouteGenerator is a small application that imports the data of MV and LV line sections from the DMS600 network database, processes the data to form section routes, and writes the results back to the network database. The application is meant to be run only once on a database that does not contain any section routes beforehand. A flowchart of the tool's functionality is presented in Figure 5.10.

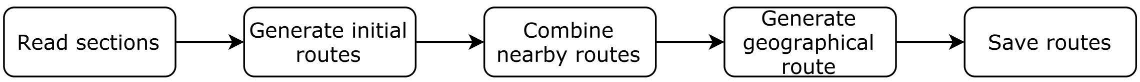

Figure 5.10 *Functionality of SectionRouteGenerator as a flowchart.*

Line sections are read in memory from the database with an SQL query that returns every segment of every line section in correct order. As the current purpose of section routes is cable trench analysis, only MV and LV underground cables are read in the query. Initial routes with geographical coordinates identical to the line sections are generated from the segments.

After the initial routes have been formed, the start and end points of each route segment are compared with other route segments in its vicinity to see if the segments should be combined to be a part of the same route. If the segments are combined, they are removed from their old routes. An example situation of route combination is shown in Figure 5.11.

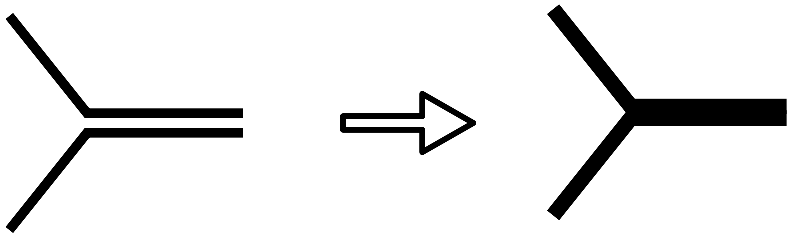

Figure 5.11 *An example of a situation where two nearby section routes are combined to one. The second segments of both routes on the left side are close enough to each other to trigger the combination, but the first segments are left as separate routes.*

When combination checks have been performed for every route, a sequence of points to represent the geographical route is generated for each route that contains remaining segments. Finally, the resulting section routes are saved to the DMS600 network database. The saved data includes both the geographical route and information about which MV and LV line section part belongs to which section route. After SectionRouteGenerator has been run, the generated section routes are immediately viewable and editable in DMS600 NE.

Settings of SectionRouteGenerator were made configurable in order to iteratively find good section route outputs. The settings in the GUI are shown in Figure 5.12.

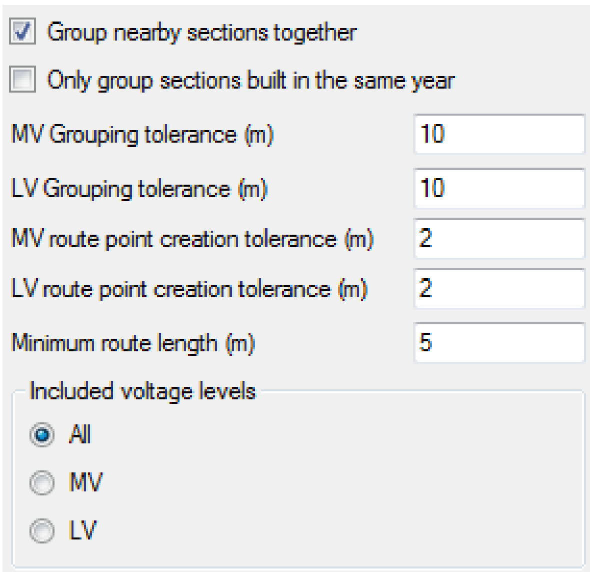

Figure 5.12 *Settings of the SectionRouteGenerator application.*

The first setting in the above figure determines if the grouping, which was illustrated in Figure 5.11, should be attempted at all. If needed, the grouping can be done based on the installation years of the MV and LV line sections that are used as a basis for the import. Grouping tolerance means the maximum allowed distance between two line segments that should be joined together to form a common section route. Point creation tolerance means the density of intermediary points that are created when forming the geographic route of the section route. Finally, minimum route length can be used to filter out section routes that would be too small. The settings can be set for MV and LV network separately, and specific voltage levels can be left out of the section route generation process as well.

5.2.3 ShapefileTool

ShapefileTool is a tool developed by ABB that performs network analysis tasks with ESRI Shapefiles. Shapefile is a spatial data format used for both town plan and CLC data as described in subsection 2.3.3. Like SectionRouteGenerator, the tool is implemented in C# language. ShapefileTool is based on a command line interface, but it can also be configured and run via ShapefileToolGUI, a .NET-based helper application that provides a graphical user interface. The user interface of ShapefileToolGUI is shown in Figure 5.13.

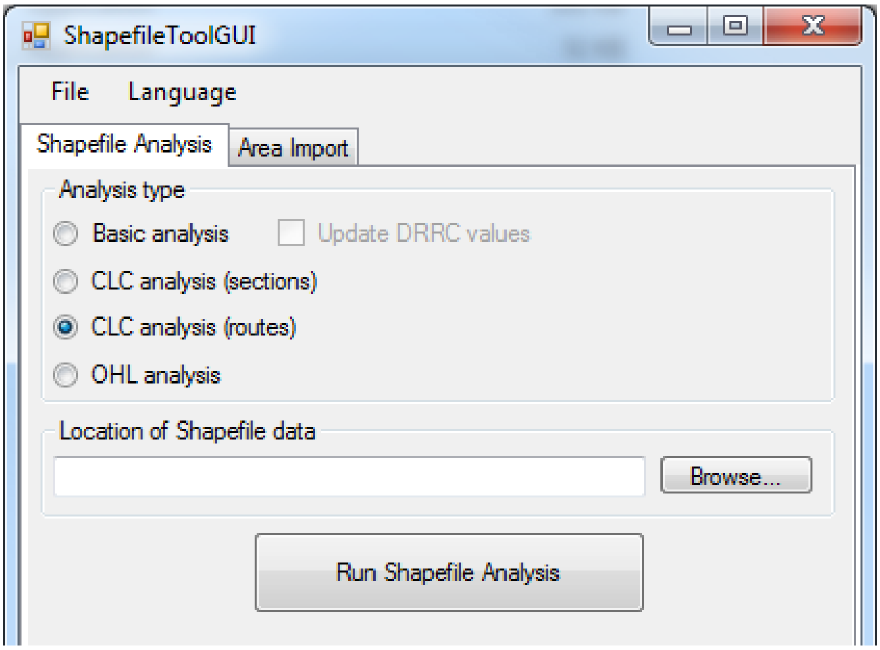

Figure 5.13 *The user interface of ShapefileToolGUI with the newest feature, environmental condition analysis of section routes selected.*

Historically, ShapefileTool has been able to analyze which nodes are located in town plan areas and to perform environmental condition analysis tasks for line sections in

MV and LV networks with the vector-based CLC data set. Since most of the mathematical functionality already existed in some form and the spatial data required for asset reports is distributed in shapefile format, the environmental condition analysis of section routes was implemented as a new feature in ShapefileTool as well.

It was decided that vector-based CLC data would be used in the calculations like in the previous regulatory periods. Vector-based CLC data is less detailed than the raster-based CLC data because the vector data by SYKE is generalized from the raster data. However, raster data cannot be used in calculations without first vectorizing it, and utilizing a vectorized data set that is too detailed and preserves the raster grid is heavy and time consuming to calculate [26]. The limitation and possible data loss was acknowledged before implementing the new feature to ShapefileTool.

Implementation of environmental analysis of section routes consisted of two major tasks. The first task was to write SQL queries and data structures to handle the section routes. With some degree of re-using existing code, the geometrical calculations that were already implemented in previous versions were able to be utilized with section routes as well.

The second task was to improve the environmental condition analysis to match the newest regulation methods. Previously ShapefileTool has only analyzed the CLC data set while discarding the town plan area data set, which results losing possible cable trench lengths in the "ordinary" category. Two implementation alternatives were considered in including both data sets in the analysis:

1. Add a possibility to ShapefileTool to load multiple shapefiles as input and perform spatial subtract operations with overlapping polygon areas.
2. Create a custom shapefile containing both town plan areas and CLC areas, but with overlapped areas already processed, and use it as an input for ShapefileTool.

The benefit of option 1 was its dynamic nature. When the spatial data sets by SYKE are updated, the input files could simply be replaced with the newest versions and the tool would work. The drawback of the option was the need to implement spatial algorithms for polygon subtraction in situations where town plan areas and difficult CLC areas overlap. In such cases, only the intersection lengths with CLC areas would be allowed to be reported.

Option 2 had the advantage of faster implementation because additional spatial algorithms did not have to be implemented. If it's assumed that no polygons overlap, differentiating the environmental areas could be done by simply inspecting individual polygons' metadata: if they include difficult CLC classes, they belong to the difficult environmental condition without doubt. As a drawback, the input data for the analysis would have to be produced manually every time SYKE updates its spatial data sets.

Ultimately, option 2 was chosen. Implementing spatial algorithms to perform calculations on polygon-shaped areas was not seen as a practical way of time management because the algorithms are already available in various open source software. Producing a new input data set for each update was not seen as a problem either, because combining shapefiles with open source Geographic Information System (GIS) software is relatively simple and the source data is not updated very often. For example, CLC data was updated in 2014 and town plan area data was updated in 2016 [12][14].

The functionality of ShapefileTool is carried out in five steps. The workflow of ShapefileTool is summarized in Figure 5.14.

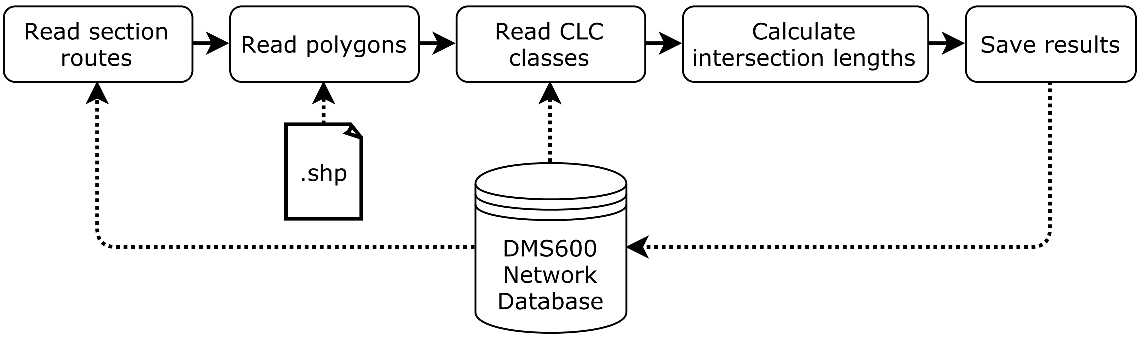

Figure 5.14 *Execution phases of ShapefileTool.*

The execution of ShapefileTool begins by reading the section routes and polygon shapes into memory. Following that, information about which CLC classes belong to which environmental condition is loaded from the network database. Polygons that are not town plan areas and do not belong to the CLC classes that were read from the database are discarded.

After all the necessary data is in memory, intersection length calculations are performed between every section route and the polygons near it. Calculation results are summed together as CLC2 (ordinary conditions) or CLC3 (difficult conditions) lengths depending on the type of the polygon. After calculations have been completed, the summed data is saved to the DMS600 network database. The lengths are saved directly to each section route, because that way the results are also viewable in DMS600 NE. The saved lengths can be grouped and summed together to generate the cable trench asset reports for the Energy Authority.

5.3 Reporting improvements

After the solutions presented in Sections 5.1 and 5.2 were developed, it became possible to develop network asset reports in SQL Server Reporting Services that match the newest reporting requirements in the regulation methods. Implementation work on the reporting definitions was done in conjunction with B.Sc Jussi-Pekka Lalli.

Existing reports were expanded to include the new ownership settings, network components and reporting type fields that were implemented in DMS600 NE. In addition, the asset reports were changed to group similar components to the categories of the regulation methods. An example of the grouping change is presented in Figure 5.15, which is a new version of the underground cable report presented in Figure 4.3 on page 29. The column in the left specified the category, which in this case is underground cable and the size of the conductor (in mm^2).

Johdintyyppi	Määrä (km)	Keski-ikä (vuotta)	Puretut (km)	Pitoaika (vuotta)
Maakaapeli 70 tai alle	38.23	5.10	0.24	40
Maakaapeli 95	83.08	2.61		40
Maakaapeli 120	153.38	15.74	0.49	40
Maakaapeli 150	23.30	3.06		40
Maakaapeli 185	164.00	2.02		40
Maakaapeli 240	11.93	4.62		40
Maakaapeli 300	4.26	9.00		40

Figure 5.15 *New DMS600 asset report for medium voltage underground cables in a Finnish customer's network. The columns from left to right are reporting category, length, average age, length of removed conductors and planned lifetime.*

The majority of report definitions were also updated to include deleted components. DMS600 NE has had the option to save every deleted component to a history table along with the date of deletion, but aside from cables and overhead lines, the information was previously never included in the reports. The new column for deleted components contains the amount of components removed in the reported year, and it was added to every report definition that didn't have the information prior to the asset management updates.

Finally, the ordering of the reports was changed to match the user interface of Energy Authority's reporting portal. This small change was made in order to simplify DSOs' work to fill in the reports and lessen the chance of human error while reporting.

6. EVALUATION

A multitude of solutions were developed in DMS600 to solve problems presented in this thesis. This chapter evaluates the developed solutions and establishes ideas for future development of asset management features in DMS600 products. Evaluation was done from the perspective of desired functionality and report data validity.

Developed solutions were internally tested with copies of customer databases. Testing with customer databases was regarded as important because different customers might have vastly different practices of using DMS600 software.

Towards the end of the development, updated copies of DMS600 executables and database scripts were delivered to the production environments of eight DSOs to help the customers familiarize themselves with the new digitizing features and to reveal possible issues that did not occur in internal tests. However, the majority of feedback is likely to be given during the reporting period in the beginning of 2018, and therefore this thesis does not focus on customer responses.

6.1 Implementation evaluation

After implementing the new network components detailed in Section 5.1, data from the components was able to be used in network asset reports. This means that the purpose of the new components was fulfilled and DMS600 customers can now digitize and report their MV and LV network assets in the level of detail that the regulatory model requires. As a result, the customers can maximize the value of their networks in the Energy Authority's calculations by being able to report more asset information.

Introducing section routes to DMS600 NE was also successful. The new network editing tools integrate to existing ones well and the data of section routes is easily retrievable for reporting purposes. As a slight drawback, the feature of linking existing MV and LV line sections to section routes creates dependencies to legacy code and decreases the performance of DMS600 NE in larger customer networks. Because asset reports in the regulatory model only require the cable trench locations and not the amount of actual cables in them, the slow behaviour could possibly have been avoided by primarily focusing on the mandatory aspects of section routes and leaving the possibility of additional functionality for a later date.

Importing section routes to customer networks with SectionRouteGenerator was less successful. Section routes that corresponded with existing underground cables were generated, but after performing route combination calculations, many errors were found in the resulting section routes. The errors caused the geographical routes to have their intermediary points in the wrong order, causing the section routes to have a cluttered appearance and wrong length. Some of the errors were fixed, but ultimately there were still so many error-causing situations in customer networks that further development of SectionRouteGenerator was halted. However, the section route import still works in smaller networks where less parallel underground cables exist. The route combination calculations can also be toggled off if needed. In those cases, nearby sections are not combined, but initial section routes are still created to some degree and they can be edited later with DMS600 NE.

On a general level, the implementation process turned out to be slower than expected especially in DMS600 NE due to technical debt from the legacy parts of the system. Another factor that slowed down the development was the lack of documentation. The final effect of technical debt can be seen only later as possible errors after the all of the developed solutions are taken to use in multiple customer environments.

6.2 Report data validation

In order to ensure that the improvements to network asset reporting were done properly, it was important to validate the results of the reports. Validation was done by performing queries on copies of customer databases and comparing the output values to ones that the customer had reported in previous years.

The biggest challenge in validating new developed reports was that DMS600 customers have filled in very little information to their network databases in the first place. Information such as conductor category or size is important from the aspect of asset reporting, but in other contexts the extra information is not of any use. Therefore some of the data produced as a comparison to older reports was not based on real customer networks, and it was difficult to see if the new reports brought changes to the calculated replacement value of the network.

As some of the existing data was not useful for testing, data was populated to the missing fields in the copies of the customer networks to test the reports. According to the tests, the reports were found to properly include the information that was populated. Customers were informed about the missing information in order to prepare them for the asset reports in 2018.

Validating the lengths of cable trenches in different environmental conditions was even more challenging. Even though section routes were implemented, DMS600 customers had not yet digitized their cable trenches to their network databases during the evaluation of the reports. In addition, the previous cable trench reports of DMS600 customers did not include the analysis of town plan areas and the reports only included cable lengths that were multiplied with coefficients used in previous regulatory periods. As a result, there were no proper new input nor old output comparison data for evaluating the results that were received from section route calculations made by ShapefileTool.

Small-scale tests with town plan and CLC areas were done in ABB's internal demo network database in order to evaluate ShapefileTool calculation results. The locations of different areas were validated with GIS software, section routes were created in the vicinity of the test areas and ShapefileTool was executed for those section routes. According to the tests, parts of section routes outside the shapefile areas were correctly assigned to easy environmental conditions, while parts inside the areas were correctly classified to ordinary and difficult conditions. However, it should be noted that if there is a small but systematic error in the calculations, its consequences will only be seen in results of large-scale cable trench analysis, which is impossible to reproduce in the current DMS600 demo environment. Another thing to note is that the calculations were based on vector-based CLC data, which is not the exact data set that's instructed to be used in the regulation methods.

6.3 Future development ideas

Most of the solutions developed during the making of this thesis were proved as working, and therefore only a change in the regulatory model might create further development needs related to the presented solutions. However, there is still a lot of manual work involved in the asset reporting process: digitizing cable trenches for new customers is not fully automatic, getting all of the data required for reports requires running separate tools and the geospatial data set used in cable trench calculations needs to be prepared manually every time the source data changes. Streamlining the data preparation process before the actual reporting is a possible target for future development activities.

Many of the features presented in this thesis were related to geospatial data. Purely from an implementation point of view, geospatial analysis would be a lot simpler if DMS600 NE was more closely integrated with GIS software. For example, the network database could utilize GIS functionality directly by storing spatial information in native GIS data types, which most DBMS vendors already support [28] [29]. Changing the data types might present an easier way to analyze network data and remove the need to implement additional tools for geospatial analysis tasks.

In a broader sense, DMS600 could be developed in a more data-driven direction. Usage of large data sets could be expanded to include hourly measured customer load data and possibly other environmental data sets. These data sets could be used for more effective network planning, which could solve problems related to distribution reliability. Improvements in distribution reliability would help fulfil the requirements of the Electricity Market Act and are directly linked to a monetary gain for DSOs, which would make the new functionality desirable.

7. CONCLUSION

The purpose of this thesis was to find and implement solutions to improve the asset management and reporting capabilities of electrical distribution network operators by developing features to ABB MicroSCADA Pro DMS600 from the aspect of authority regulation. At first, the authority regulation methods and customer feedback were examined to identify changes that have been made to the methods since the previous update to DMS600 asset management capabilities or find asset management features that are otherwise missing from the product. After the development needs were formulated, the implementation phase began. Solutions were implemented in all levels of the product. Changes were made to the underlying database, the program user interface and asset report definitions. Additional tools were also created and updated in order to process and prepare data for the asset reports better. The developed solutions were then tested with both internal test environments and customer environments, and the reports were verified by comparing them with older reports that DMS600 customers had submitted in previous years.

The goal of updating DMS600 reporting capabilities to match the newest regulation methods was achieved. Some hindrances were experienced during the development process due to some technical debt in the system, but the needed solutions were able to be implemented and tested. Implementing the solutions enabled DMS600 customers to report all medium voltage and low voltage network assets according to the categories that the Energy Authority has determined in the regulation methods. By being able to report their network assets fully, the customers can maximize the profit they are allowed to make in the regulatory model.

According to tests that were carried out with the new features, the biggest issue in distribution system operators' reporting capabilities is the fact that not enough detailed information has been saved to network databases. As a result of the lack of details, not all information required by the authority regulation methods can be retrieved and processed immediately from the existing networks. In order to utilize the automated reports by DMS600, customers were instructed to update the required details in their databases.

In the future, ways to streamline and automate the reporting process could be developed to minimize the need for human intervention. DMS600 could also be developed in a direction where analysis tasks are performed as back-end database operations, which could provide more dynamicity if the regulation methods change. In general, data-driven approaches could be investigated in the development of DMS600 to provide distribution system operators with better tools to plan and operate their electrical distribution networks.

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